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Assessment of Midair Collision Risk and Safety Benefits of TCAS II for Cargo Aircraft

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Mitre report

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Section 1

Introduction

At the request of the Federal Aviation Administration (FAA) Office of Aviation Policy, we conducted a study of historical midair collision risk, factors affecting ongoing risk, and the potential safety improvements that Traffic Alert and Collision Avoidance System (TCAS II) could provide if installed on cargo aircraft.

There are many levels of safety built into the Air Traffic Control (ATC) system that guard against the risk of midair collision. However, when human errors by pilots or controllers, or equipment failures occur, safety margins sometimes erode. In some instances, separation between aircraft is lost. Many different factors apply in such cases. These could include a pilot's lack of awareness of nearby traffic, a navigational error, or confusion concerning the intentions of other traffic or the parameters of his own clearance. There is such variety of circumstances that it appears no single measure can entirely eliminate the collision risk.

Nevertheless, TCAS II has proven effective in providing additional protection against collision. TCAS II was designed to supplement the safety margins of the ATC system by providing protection when other means may fail. At present, TCAS II is required to be carried on passenger airlines and has also been voluntarily installed on a small fraction of military transport and on General Aviation (GA) (primarily business) aircraft.

Numerous reports have been filed attesting to occasions where safety benefits were gained from using the TCAS equipment. Often, these reports suggest that TCAS served as the final safety net that prevented an accident. Reports also disclose that a pilot's and a controller's view of a situation may differ in various ways, particularly in the degree of imminent danger associated with a loss of separation.

The report examines historical rates of collisions and reported near-collisions. Due to the voluntary nature of reporting and the subjective method of classifying incidents, the statistics for near-collisions must be taken with caution. These statistics and the forecast trends of traffic growth are used to develop estimates of future collision rates, including statistical bounds indicating their uncertainty, for various user categories. Finally, we use the results of widely accepted TCAS logic analysis to estimate the reduction in collision risk that could be achieved if the fleet of cargo carriers were to equip with TCAS II.

The potential benefits of TCAS II have been studied by extensive computer simulations and validated by tens of millions of hours of operational experience. These safety benefits have been recognized by International Civil Aviation Organization (ICAO) in its worldwide mandate for TCAS II[1] installation, which affects both passenger and cargo carriers. In the United States (U.S.), TCAS II installation in passenger carriers began in 1990, with full equipage reached by the end of 1993, for carriers with more than 30 seats. There have been no midair collisions involving TCAS-equipped aircraft in the U.S.

1.1 How TCAS Reduces the Risk of Midair Collision (MAC)

1.1.1 Collision Risk Factors to Traffic in General

Air traffic is organized in widely varying regimes, but always with great attention toward minimizing the risk of MAC. In controlled airspace, which comprises the great majority of flight hours for passenger carriers, air traffic specialists monitor positions and issue clearances designed to preserve separation. The controllers are aided by radar in nearly all of domestic airspace; but even where radar is unavailable, they maintain order through their clearance structure and by monitoring flight progress. Flight over the oceans is a prime example of an orderly flow conducted without the benefit of ATC radar.

Uncontrolled airspace, which is typical of much recreational flying, relies upon a pilot see-and-avoid discipline to a great extent, since the aircraft follow less structure to their routes. With great variations occurring in meteorological conditions and aircraft conspicuity, as well as a variety of closing speeds that is inherent as aircraft approach one another from various directions, see-and-avoid cannot be considered a highly reliable means of protection. Adding to the unreliability are the presence of nonprofessional pilots, who may have limited experience in their current aircraft or may be in unfamiliar locales, and may more frequently suffer distractions and confusion. Though the latter factors could also affect professional pilots, their risk is minimized by the use of 2-person crews and disciplined flight procedures. Small airports often are uncontrolled, with the pilots' see-and-avoid discipline supplemented by the protocols of announcing their operations on a common radio channel, and entering airport landing patterns in a uniform manner.

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[1] The ICAO terminology for TCAS is for Airborne Collision Avoidance System (ACAS).

Another risk occurs when an inexperienced pilot strays into controlled airspace without permission, and sometimes without the safety equipment required in that airspace. In areas surrounding the largest airports, where traffic tends to be dense and arrival/departure throughput has great economic consequences, the ATC system has imposed strict "Terminal Control Area" boundaries and rules. These require, among other things, that all aircraft fly under ATC control and carry transponders, allowing them to be tracked by ATC radar as well as by TCAS.

Finally, from time to time there are episodes of controller errors leading to losses of separation. Another cause results from a failure of ATC equipment (e.g., radar, communications).

1.1.2 Collision Risk Factors for Cargo Carriers

Cargo carriers experience many of the same risk factors as other types of air traffic, though not necessarily in the same proportions. They fly similar aircraft types compared to passenger carriers, and their crews have generally the same characteristics and skills. The factors of situational awareness, workload, and human error can apply to them.

A difference in risk exposure may be hypothesized because the cargo carriers tend to concentrate their flying at night, and use hub operations that are mostly separate in location from the passenger hubs. Of course, the nature of freight traffic requires that their aircraft fly throughout the airspace, conducting some operations at most major hubs. Also, in nighttime flying, the tasks of visual acquisition and identification of traffic differ in some ways from daylight operations, and have unique failure modes.

Section 4 of this study analyzes flight data to quantitatively measure the exposure cargo carriers have to other types of airspace users, by location and time of day. This analysis may even underestimate their exposure to GA, since recreational Visual Flight Rules (VFR) flights are not included in the database, and the analysis uses terminal operations only. Cargo flights generally traverse enroute airspace and have various opportunities for mixing with GA aircraft.

1.2 TCAS Functions

Many near-collision reports cite the pilot's lack of awareness of the conflicting traffic. To address this need, TCAS provides a Traffic Display, which shows nearby transponder-

Section 3 examines the flying done by various classes of users and estimates the present levels of risk, as well as the future risk for forecast traffic levels, assuming collision avoidance avionics equipage remains as it is today. To assist in any assessment that may be performed of TCAS benefits, the geographic distribution of historical collisions is examined. This could assist in estimating the collateral damage that might result from a collision.

Section 4 examines air traffic statistics for a number of busy areas, including passenger and cargo hub airports. It determines the exposure between the various user types by place and time of day. The results of TCAS safety analyses are applied to determine the overall collision risk reduction that could result from cargo carrier equipage.

Section 2

History of MACs and Near Midair Collisions (NMACs)

2.1 Introduction

Section 2 reviews the recent history of MACs and NMACs in the National Airspace System (NAS). In order to illustrate the grounds for concern about MACs, the discussion begins by describing a catastrophic MAC that occurred over Cerritos, CA, in 1986. In order to illustrate the continuing risk of MACs and in particular of MACs involving cargo airliners, a recent near midair collision is also described. Then comments about the TCAS in Aviation Safety Reporting System (ASRS) reports of NMACs are quoted to illustrate the utility of TCAS in NMAC situations.

The balance of Section 2 is devoted to a statistical analysis of MACs and NMACs, which is used in Section 3 to estimate probabilities of MACs between aircraft of three different types: passenger airliners currently required to use TCAS II, large cargo airplanes not currently required to use TCAS II, and other aircraft.

2.2 The 1986 Cerritos MAC

At about 11:52 Pacific daylight time Aeronaves de Mexico flight 498, a DC-9-32, and Piper N4891F, a PA-28-181, collided over Cerritos, CA, at an altitude of about 6,560 feet mean sea level. The sky was clear, the reported visibility was 14 miles, and both airplanes fell within the city limits of Cerritos. Fifty-eight passengers and 6 crewmembers on flight 498 were fatally injured as were the pilot and 2 passengers on the Piper. The wreckage and post-impact fires destroyed five houses and damaged seven others. Fifteen persons on the ground were killed and 8 others on the ground received minor injuries.

Flight 498 was a regularly scheduled passenger flight between Mexico City, Mexico, and Los Angeles International Airport via Guadalajara, Loreto, and Tijuana, Mexico. The Piper had departed Torrance, CA airport on a visual flight rules flight to Big Bear, CA.

Recorded air traffic control radar data revealed that, after departing Torrance, the Piper pilot turned to an easterly heading toward the Paradise VORTAC. The on-board transponder was active with a 1200 code. Post-accident investigation revealed that as the Piper flew eastbound it entered the Los Angeles Terminal Control Area (TCA) without receiving clearance from air traffic controllers required by Federal Aviation Regulations. The midair collision occurred within the confines of the Los Angles TCA.

The National Transportation Safety Board (NTSB) determined that the probable cause of the accident was the limitations of the ATC system to provide collision protection, through both ATC procedures and automated redundancy. Factors contributing to the accident were (1) the inadvertent and unauthorized entry of the PA-28 into the Los Angeles TCA and (2) the limitations of the "see and avoid" concept to ensure traffic separation under the conditions of the conflict.

2.3 A Recent NMAC Between Cargo Airliners

Two U. S. airline cargo aircraft nearly collided at flight level 330 over Kansas on 3 March 1999. A Federal Express McDonnell Douglas DC-10 had departed from Portland, OR, and was en route to Memphis, TN. The other aircraft was an American International Airways Lockheed L-1011 which had departed from Los Angeles, CA, and was proceeding to Indianapolis, IN. The minimum distance between the two aircraft at the time of the near-collision was reported as a quarter-mile (ATC recorded radar data) or as 50–100 feet (crew member estimate). The DC-10 captain reported that he never saw the L-1011 approaching. The L-1011 crew members saw the DC-10 to the left and slightly behind them at nearly the same altitude and took evasive action to avoid a collision.

An investigation of the near-collision determined that air traffic controllers in two different air route traffic control centers failed to properly transfer control and radio communications for both aircraft to the next sectors that the flights would fly through according to their flight plans. As a result, both aircraft were not on the proper radio frequency (under no one's control) as their flight paths converged at the same altitude over Kansas. While ATC was aware of the pending conflict the controllers were unable to issue control instructions to separate the two aircraft because they could not communicate with the flight crews on the proper radio frequency.

The near-collision also highlighted a difference in the requirements for onboard collision avoidance systems between passenger and cargo flights. Currently, regulations require all large passenger carrying aircraft (31 passenger seats or more) operating in U. S. airspace to be equipped with an airborne collision avoidance system which alerts flight crews of potential conflicts and, if necessary, instructs them to climb or descend to resolve the conflict. The system is called TCAS II. Large cargo carrying aircraft are not currently required to be equipped with TCAS II.

2.4 Trends of MACs and NMACs

Figure 2.1 shows the trend in annual collisions and near midair collision reports. It is seen that the near midair reports are decreasing at a greater rate than the collisions. Table 2-1 lists the numbers of injuries associated with these collisions. Note that for years 1994-97, when TCAS was carried onboard passenger airlines, collisions and injuries continued to occur for other aircraft types.

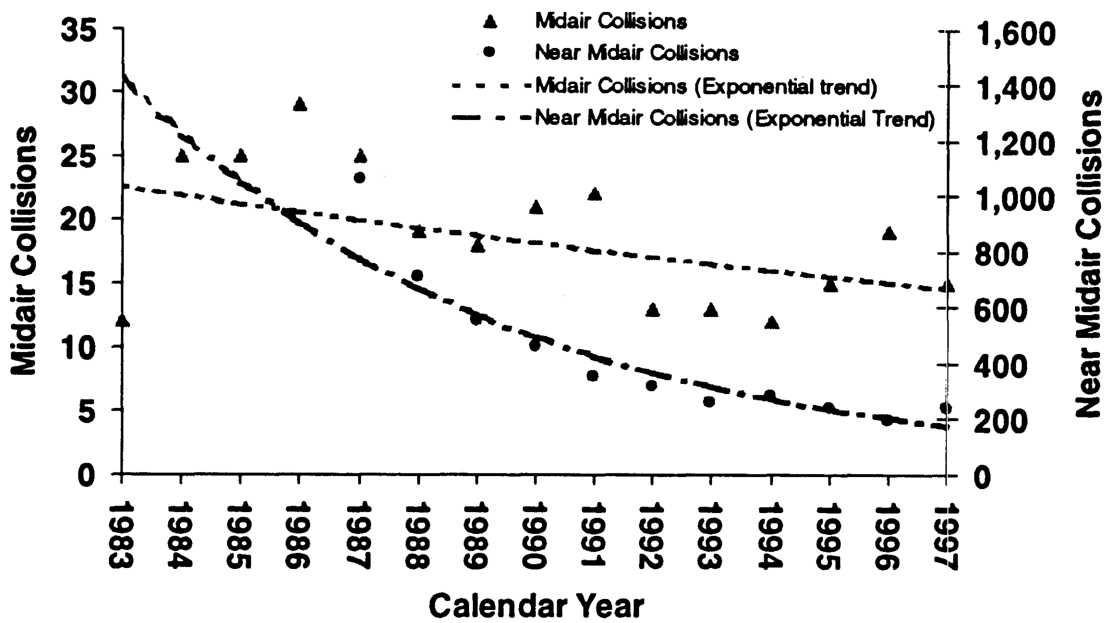

Figure 2.1 MAC and NMAC Trends

Data source: FAA/ASY-100, *Aviation System Indicators*, Nov. 15, 1998.

Table 2-1 Injuries to Persons Involved in MACs in the NTSB Aviation Accident/Incident Database

	Injury Severity			
Period	**Fatal**	**Serious**	**Minor**	**None**
1983-April 28, 1999	572	79	111	573
1994-1997	92	6	20	103

2.5 Comments About TCAS in Aviation Safety Reporting System (ASRS) Reports of NMACs

Pilot reports shed light on the value of TCAS II in the present ATC system. When conditions become difficult, normal operations can break down to some extent. Pilot reports in the National Air and Space Administration (NASA) ASRS are instructive as to the range of errors that may lead to reduced separation and the resulting burden on the pilots to exercise see-and-avoid.

One set of NMAC reports primarily appeared around 1991, when TCAS II was being installed on passenger aircraft. Pilots who did not yet have the system described a number of close calls where they believed they needed its protection. The circumstances frequently concerned either another aircraft unknown to ATC, or an uncontrolled aircraft making a dangerous maneuver. If controller workload or frequency congestion complicated operations, pilots complained of the resulting risk. Similarly worded reports have begun to appear in recent years from pilots of cargo or freight airlines, who likewise call for TCAS II to be installed on their aircraft.

Other reports praised TCAS II after its installation. Some of these are excerpted below:

> "I THEN GLANCED AT THE TCAS DISPLAY SCREEN AND, IN DISBELIEF, OBSERVED THAT THE OTHER ACFT WAS CLBING...I SLAMMED BOTH THROTTLES TO THEIR STOPS AND RAPIDLY PULLED THE NOSE UP...THE OTHER ACFT WAS 300 FT BELOW US AND STILL CLBING. I AM NOW A FIRM BELIEVER OF THE TCASII SYS. I HATE FLYING WITHOUT IT."

"ALTHOUGH OUR TCAS SHOWED THAT THE HELI PASSED 300 FT DIRECTLY BELOW US WE NEVER SAW HIM AS WE WERE JUST COMING OUT OF THE CLOUDS BASES...I FEEL THAT WITHOUT THE TCAS IF WE HAD CONTINUED OUR 800 FPM DSCNT RATE IT WOULD HAVE RESULTED IN MID AIR COLLISION OR VERY CLOSE TO ONE."

"THE RFD WARNING TFC SYMBOL ON OUR SCOPE WAS RAPIDLY OVERTAKING US...HE PASSED NO MORE THAN 50-75' OVERHEAD, AND THEN AS WE MADE A SHALLOW TURN TO THE RIGHT HE PASSED IN FRONT OF US...I BELIEVE THE TCAS SAVED OUR LIVES AND IN RETROSPECT I WISH I HAD FOLLOWED ITS ADVISORIES MORE AGGRESSIVELY.

"THERE WERE A LARGE NUMBER OF ACFT IN THE VICINITY...I'M SURE THE CTLR'S RADAR SCREEN WAS A WASH WITH TFC. THE TCAS WORKED WONDERFULLY...I WAS GLAD THE SYS WAS OPERATIONAL. TCAS NOT ONLY POINTED OUT THE CONFLICT FASTER THAN VIS" "ACQUISITION, BUT ALSO MADE OUR EVASIVE ACTIONS SMOOTHER AND MORE TEMPERED."

"I FEEL THAT TCAS AVERTED A POSSIBLE MID AIR DUE TO ATC BREAKDOWN IN COM. THERE HAD BEEN NO ADVISEMENT OF THE TFC."

"HAVING NEVER SEEN THE TFC, I CAN ONLY ESTIMATE THE DISTANCE OF THE NEAR MISS AT 300-400'...WE WERE DSNDING TO THE W AND LOOKING FOR THE TFC INTO THE GLARE OF THE SETTING SUN. THANK GOODNESS FOR TCAS!"

"THE F/O AND I WERE UNABLE TO LOCATE THE TFC VISUALLY...WE RECEIVED A TCAS RA...THE F/O SAW THE TFC OUT HIS SIDE WINDOW...THE INCIDENT ENCOUNTERED WAS A NEAR MISS, AND HAD IT NOT BEEN FOR TCAS, COULD HAVE HAD DISASTROUS RESULTS."

"I THEN SAID VERY FIRMLY TO HIM THAT I HAD JUST EXPERIENCED A "NEAR MISS,"... THE SUPVR ANSWERED...A BRAND NEW RADAR CTLR HAD GOTTEN OVERLOADED AND FORGOTTEN THE ARMY HELI...I VOTE FOR TCAS."

2.6 Statistics of MACs

This section reviews the statistics of MACs involving U.S. certificated aircraft or large foreign air carrier aircraft operating in the NAS. The data were obtained from the NTSB Aviation Accident/Incident Database. The purpose of the review is to provide a basis for estimating rates and probabilities of MACs between aircraft. In this study we classify aircraft in three categories:

P: Passenger airliners currently required to use TCAS II

C: Large cargo airplanes not currently required to use TCAS II

O: Other aircraft

For purposes of this analysis, category C is defined as airplanes operated under 14 CFR 121 or 14 CFR 129 having no more than 30 passenger seats and having a certificated maximum gross weight greater than 33,000 lb. Category P is defined as aircraft operated under 14 CFR 121 or 14 CFR 129 having more than 30 passenger seats.[i] Category O is defined as all other aircraft.

The NTSB Aviation Accident/Incident Database is the most authoritative and comprehensive database of reports on accidents, including MACs, involving U.S. civil aircraft, U.S. public aircraft (except military and intelligence aircraft), and foreign aircraft operating in the U.S., its territories, or possessions. 49 CFR 830.5 requires the operator of any such aircraft to immediately notify the NTSB of an accident (or of certain incidents) involving such aircraft. 49 CFR 830.15 requires a report to be filed within ten days. Counting such reports, even if they are only preliminary reports, is probably the best method of counting MACs. The database contains reports on MACs involving U.S. aircraft outside of U.S. airspace; these will be excluded from the estimates of collision rates and probabilities derived below.

MACs that occurred from 1994 through 1997 are of particular interest in this analysis, because (1) category P aircraft have been required to carry TCAS II throughout this period,[ii] and (2) for those years data on U.S. air carrier flight hours and total system [NAS] flight hours are available and can be used in the denominators of accident rates, which are calculated in the following section.

The next paragraphs summarize statistics of all MAC reports in the online NTSB Aviation Accident/Incident Database as of 1 June 1999. The following paragraphs provide a more detailed summary of the reports of MACs that occurred from 1994 through 1997.

2.6.1 MACs from 1 January 1983 to 2 May 1999

On 1 June 1999, the online NTSB Aviation Accident/Incident Database[iii] had data as of 2 May 1999. It contained a total of 42,487 reports, including 40,964 accident reports. Of these, 605 were reports for aircraft involved in a MAC.[iv] Six of the reports were designated "Cargo" aircraft,[v] 18 were for "Passenger/Cargo" aircraft, six were for "Passenger" aircraft, and the remaining 575 were for aircraft not identified by any entry in the "Passenger/Cargo" field of the report. Of those 575, 548 listed GA as the category of operation; the other 27 reports also described type O flights.

The six reports for "Cargo" aircraft describe five MACs, all of which were O-O collisions. Two reports are for aircraft involved in the same collision. Both were Gulfstream GA-500-B aircraft, each with two seats and a Certificated Maximum Gross Weight of 6750 (lb.) operated under the provisions of 14 CFR135. Both aircraft are therefore classified as category O aircraft for purposes of this analysis. One report describes a Cessna CE-310-R operating as a Part 135 cargo flight, which collided with a Cessna 185B piloted by a private pilot. This is classified as an O-O collision. One report describes a six-place Piper PA-60-600 operated as a Part 135 cargo flight by Federal Armored Service, which collided with a four-place Piper PA-28 conducting instrument training under VFR. This is classified as an O-O collision. One report describes a large two-place Aerospatiale AS350D Helicopter operated as an unscheduled Part 135 cargo flight, which collided with a Cessna 206 operating as a GA flight. This is classified as an O-O collision. One report describes a Beech BE-18-XXX operated as a non-scheduled Part 135 cargo flight, which collided with another Beech BE-18-XXX operated as a GA flight. This is classified as an O-O collision.

Only eight of the 605 reports were for aircraft with a certificated maximum gross weight greater than 33,000 pounds. Seven of the eight reports describe O-O collisions. One report describes the 109,000-lb DC-9 in the Cerritos collision, a P-O collision. However, 44 reports listed "0" for the certificated maximum gross weight or left the field blank; one of these was the report[vi] for a Boeing 727 involved in a collision in Guadalajara, Mexico. It is notable that this accident involved one aircraft without an operating ATC transponder.

Table 2-2 summarizes the results of our analysis. Only one MAC involved a passenger carrier; none involved a large cargo carrier; and the remainder were class "O" for the purpose of this study. The collision in Guadalajara is excluded.

Table 2-2 MACs in the U.S., 1 Jan. 1983, to 2 May 1999

Collision Type	Collisions
P-P	0
P-C or C-P	0
P-O or O-P	1
C-C	0
C-O or O-C	0
O-O	301

2.6.2 MACs From 1994 to 1997

Of the 605 MAC reports in the NTSB database, 121 are for MACs that occurred between 1 January 1994, and 31 December 1997. Of the 121, 3 are for "Passenger" aircraft, none are for "Passenger/Cargo" aircraft or "Cargo" aircraft, and no Passenger/Cargo type is specified for the other 118 aircraft. The 118 reports are for 61 collisions; 60 of which have pairs of reports (one per aircraft involved) in the database. One report has no counterpart; it describes the collision of a 1-place Fokker with an unidentified airplane. According to a witness, the planes were flying in formation, so this is assumed to have been an O-O collision.

The three reports[vii] for Passenger aircraft describe two O-O collisions. One report describes a collision of two Britten-Norman BN-2s. Two reports describe a collision of a 4-place helicopter with a Cessna 185.

Table 2-3 summarizes the counts of MACs that occurred in the U.S., its territories, or possessions, by collision type. Figure 2.2 shows the distribution of these MACs by state and territory. None occurred outside the U.S., its territories, or possessions, during this period.

Table 2-3 MACs by Collision Type, 1994-1997

Collision Type	Collisions
P-P	0
P-C, C-P	0
P-O, O-P	0
C-C	0
C-O, O-C	0
O-O	61

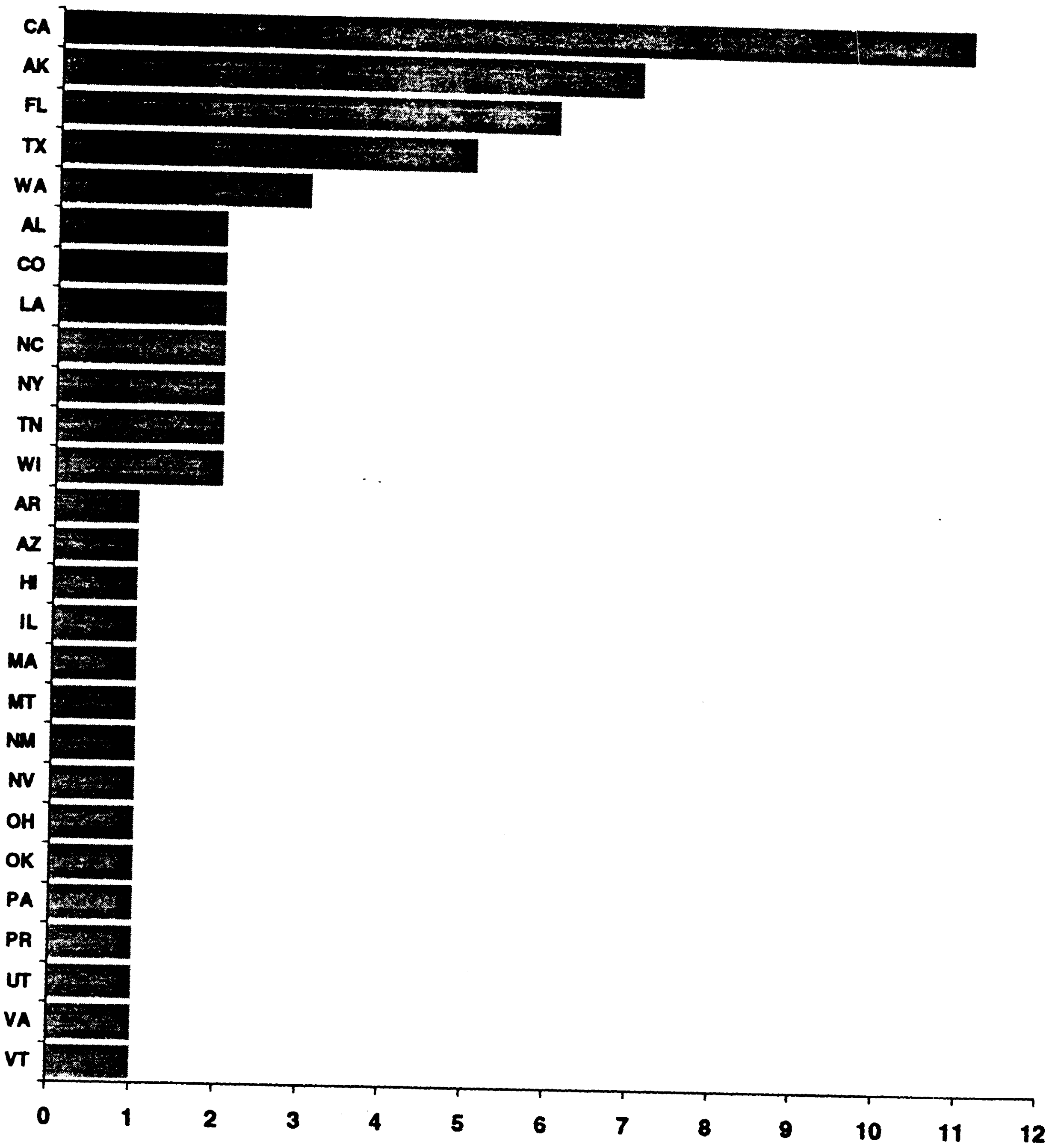

Figure 2.2. MACs per State, 1994 to 1997

Table 2-4. MACs Locations, 1994 to 1997

Location	Location (continued)
NONDALTON, AK	CHICAGO, IL
NAKNEK, AK	OIL CITY, LA
STERLING, AK	INTRACOASTAL CITY, LA
ANCHORAGE, AK	MARLBOROUGH, MA
HEALY, AK	BOZEMAN, MT
NUNAPITCHUK, AK	ASHEBORO, NC
TATITLEK, AK	ROBBINS, NC
FORT PAYNE, AL	ALBUQUERQUE, NM
GULF SHORES, AL	RENO, NV
PROCTOR, AR	EAST FARMINGDALE, NY
MESA, AZ	HAMPTON BEACH, NY
BANNING, CA	MIDDLETOWN, OH
OAKDALE, CA	BARTLESVILLE, OK
SANTA PAULA, CA	MONONGAHELA, PA
RAMONA, CA	FAJARDO, PR
PACIFICA, CA	PARIS, TN
RAMONA, CA	ARLINGTON, TN
LOS ALAMITOS, CA	PEARLAND, TX
NAPA, CA	SAN ANTONIO, TX
TRUCKEE, CA	WESLACO, TX
SAN DIEGO, CA	CADDO MILLS, TX
EL CAJON, CA	TYLER, TX
ENGLEWOOD, CO	CLINTON, UT
BOULDER, CO	KIPTOPEKA, VA
OKEECHOBEE, FL	HIGHGATE, VT
NEW SMYRNA BEACH, FL	AUBURN, WA
OCALA, FL	SPOKANE, WA
FLAGLER BEACH, FL	ARLINGTON, WA
ST AUGUSTINE, FL	OSHKOSH, WI
TAMPA, FL	NEWTON, WI
HONOLULU, HI	

For the purpose of estimating collateral damage resulting from a collision, it may be useful to consider the locations of previous collisions (Table 2-4) and the corresponding population statistics of these locations (Table 2-5). It is seen that most of the collisions did not occur at major hub locations where traffic is dense. This implies that the risk is geographically widespread. We reiterate that this data set contained only O-O type collisions. This group includes GA, Air Taxi, and Military aircraft.

Table 2-5. Population Distribution of MACs, 1994 to 1997

Type of Location	Midair Collisions
City (over 100,000 pop.)	10
Small City or Suburban (10,000-100,000 or close to a city)	23
Rural or Low-Density (under 10,000 pop.)	28

2.7 Statistics of NMACs

This section reviews the statistics of NMACs, focusing on those reported in the FAA's Near Midair Collisions System (NMACS) database. Other databases, such as the ASRS, the FAA Incident Data System (FIDS), and the NTSB Aviation Accident/Incident Database, also have reports of NMACS. None of these are comprehensive, because reporting of NMACS is not mandatory. Use of any NMAC data for risk assessment requires inferring or judging relationships between reported NMACs and NMACs, and between NMACs and MACs. This chapter summarizes the NMACs in the NMACS database, because it is based on reporting and investigation procedures developed specifically for NMACs.

On 2 June 1999, the online NMACS database[viii] contained data as of 5 February 1999. It contained 1,726 reports. The earliest NMAC in the database occurred 2 January 1992; the most recent occurred 27 January 1999. During this period, 102 MACs are reported in the NTSB Aviation Accident/Incident Database (in 203 MAC reports), so the ratio of MACs to reported NMACs was 0.059 for this period. 943 of the 1,726 reported NMACs occurred between 1 January 1994, and 31 December 1997. For this period the ratio of MACs to reported NMACs was 0.065.

Operator codes deemed to be cargo carrier codes are shown in Table 2-6.

Table 2-6. Cargo Operator Codes in the NMACS Query Form

ABX Air, Inc. (Airborne Express)	ABXA
Air Alaska Cargo, Inc.	SLIA
Air Transport International	IXXA, QGQA
American International Airways	AKBA, CKSA, WOEA
Atlas Air	UIEA
Capital Cargo International Airlines, Inc.	C8GA
Challenge Air Cargo	CLCA
DHL Airways	DHLA
Emery Worldwide	RRXA
Evergreen International Airlines	EIAA
Federal Express	FDEA
Fine Airlines	FXLA
Gemini Air Cargo, Inc.	G6OA
Gulf and Caribbean Cargo, Inc.	VGCA
Lynden Air Cargo L L C	LR7A
Mountain Air Cargo, Inc.	MTNA
Northern Air Cargo, Inc.	NACA
Polar Air Cargo	P5CA
Ryan International Airlines	RYNA
Southern Air Transport	SRAA
United Parcel Service	IPXA

These 21 carriers (24 codes) include all but three (Cargolux Airlines International, Nippon Cargo Airlines, and Volga-Dnepr Airlines) of those identified as cargo airlines in the 1997 study; they also include seven carriers not identified in the 1997 study: Air Alaska Cargo, Inc.; Capital Cargo International Airlines, Inc.; Gemini Air Cargo, Inc.; Gulf and Caribbean Cargo, Inc.; Lynden Air Cargo L L C; Mountain Air Cargo, Inc.; and Northern Air Cargo, Inc.

All other codes in the form were deemed to be noncargo air carriers.

2.8 Endnotes

[i] Public Law 100-223 and Public Law 101-236, codified at 49 USC Sec. 44716.

[ii] 14 CFR 129.18 prohibited any foreign air carrier from operating a turbine-powered airplane having more than 30 passenger seats in the United States after December 30, 1993, unless it is equipped with TCAS II and the "appropriate class of Mode S transponder."

[iii] FAA, as of June 1, 1999, "NTSB Aviation Accident/Incident Database,"

http://nasdac.faa.gov/asp/asy_ntsb.asp .

[iv] Specifically, a search for Search String: "MAC: YES" with Event Type: Accident found 605 reports.

[v] A search for Search String: "Passenger/Cargo: CARGO" AND "MAC: YES" with Event Type: Accident found 6 reports.

[vi] Report FTW93WA107A describes the collision of a Boeing 727 in Guadalajara, Mexico.

[vii] The numbers of the reports describing "PASSENGER" aircraft are ATL97FA113A, ANC96LA111A, and ANC96LA111B.

[viii] FAA, as of June 2, 1999, "NMACs,"
http://nasdac.faa.gov/asp/asy_nmacs.asp

Section 3

Statistical Estimates of Present and Future Collision Risk

3.1 Introduction

This section presents a statistical analysis of collision risk that is based upon the number of flight hours flown by a given segment of the aviation community, focusing particularly on the estimated risk for Cargo Carriers. Because of the comparatively small number of hours flown by the Cargo Carriers, the absence of midair collisions in the time frame examined, and the fact that this analysis does not account for mitigating effects such as the fact that cargo operations are conducted under Instrument Flight Rules (IFR) in an ATC-controlled environment primarily at night when exposure to other aviation is limited, the uncertainty bounds for estimates of collision risk are large. The primary point of this analysis is that while no collisions have occurred during the time frame examined, the risk of collision is nevertheless not zero and is projected to increase with increasing numbers of flight hours in the years ahead.

3.2 Collision Risk

This section describes the calculation of collision rates for the collisions defined in Section 2. For each type of collision, the collision rate is defined as the number of MACs that occurred per year in the U.S. from 1994 through 1997, divided by the product of the number of flight hours flown per year by aircraft in the first category (e.g., C) and the number of flight hours flown per year by aircraft in the second category (e.g., P). Form 41 data[ix] are used to estimate flight hours for categories P and C. Flight hours for category O are estimated by subtracting flight hours for categories P and C from the [National Airspace] System Flight Hours tabulated in the FAA *Aviation System Indicators* report.[x]

Form 41 flight hour data were found for the cargo carriers listed in Table 3-1.

Table 3-1. Form 41-Reporting Cargo Carriers

Air Transport International Limited Liability Co.	QGQA, IXXA
American International Airways, Inc.	WOEA, AKBA, CKSA
Atlas Air, Inc.	UIEA
Capital Cargo International Airlines, Inc.	C8GA
Challenge Air Cargo, Inc.	CLCA
DHL Airways, Inc.	DHLA
Emery Worldwide Airlines, Inc.	RRXA
Evergreen International Airlines, Inc.	EIAA
Federal Express Corp.	FDEA
Fine Air Services Inc.	FXLA
Gemini Air Cargo, Inc.	G6OA
Lynden Air Cargo L L C	LR7A
Northern Air Cargo, Inc.	NACA
Polar Air Cargo, Inc.	P5CA
Ryan International Airlines, Inc.	RYNA
Southern Air Transport, Inc.	SRAA
United Parcel Service Co.	IPXA

ABXA, MTNA, SLIA, and VGCA are not Form 41-reporting carriers.

The Form 41-reporting cargo carriers flew 4,169,244 hours from 1994 through 1997. This is used as an estimate of category C flight hours, although it may be an overestimate, as explained below. All Form 41-reporting carriers flew 54,244,779 hours from 1994 through 1997; subtracting the estimate of category C hours from this yields an estimate of category P hours: 50,075,535 flight hours from 1994 through 1997. Subtracting total Form 41 flight hours from System Flight Hours (167,547,595) to obtain the flight hours (113,302,816) for category O for this period. Figure 1 shows these values normalized to annual rates.

This count of flight hours, and the Bureau of Transportation Statistics (BTS) table from which it is derived, exclude flight hours reported by foreign air carriers on Form 41 Schedule T-100(f), some fraction of which are flown in the NAS. This undercounting of Part 129 flight hours causes overestimation of P-P, C-C, and P-C collision rates and probabilities to an unknown degree. The exemption of cargo-only carriers from Form 41 reporting requirements leads to additional underestimation of cargo carrier flight hours and overestimation of C-C and P-C (and possibly C-O) collision rates. Because category O flight hours are calculated as a residual, the undercounting of C and P flight hours causes overestimation of O flight hours and underestimation of O-O collision rates and probabilities to an unknown degree. The undercounting of P and C flight hours and overestimation of O flight hours may lead to either overestimation or underestimation of P-O and C-O collision rates and probabilities.

Table 3-2 presents, for each pair type, the product of flight-hours for that type, the collision rate that was observed, and an upper confidence limit reflecting the statistical uncertainty in estimate the actual rate.

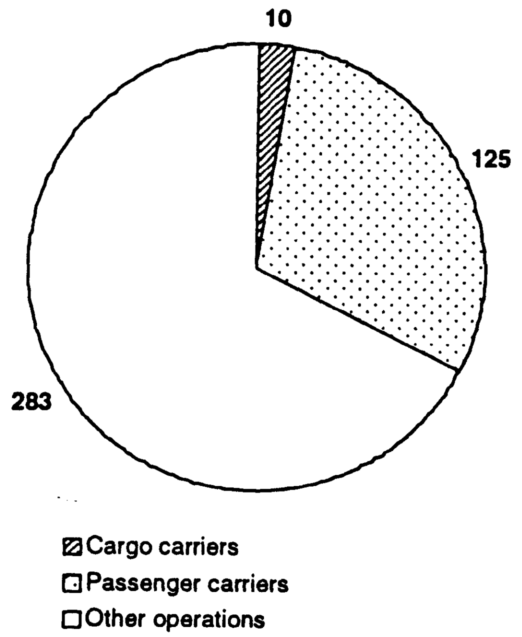

Figure 3.1. Average Annual Flight Hour Rates (100,000 hr/yr) of Large Cargo Carriers, Large Passenger Carriers, and Other Operators, 1994 to 1997

Table 3-2. Collision Rates and Probabilities, 1994 to 1997

Collision Type	Flight Hour Rate Product $(100{,}000\ hr/yr)^2$	MACs in U.S.	MACs per year per $(100{,}000\ hr/yr)^2$	Upper 90 percent Confidence Limit on Probability of MAC per year per $(100{,}000\ flight\ hours/year)^2$
O-O	80,235	61	0.00019	0.00090
P-O, O-P	35,461	0	0.00000	0.000065
P-P	15,672	0	0.00000	0.00015
C-O, O-C	2,952	0	0.00000	0.00078
P-C, C-P	1,305	0	0.00000	0.0018
C-C	109	0	0.00000	0.021

This collision rate has units of collision-years per squared flight hour. The corresponding collision probability is a probability of collision per year, per flight hour rate (flight hours per year) squared. Other things being equal, the cumulative probability of a collision, or the expected number of collisions, increases with elapsed years (like a Poisson process) as well as with the flight hour rate of the first type of aircraft (which is proportional to the average density of target aircraft) and with the flight hour rate of the second type of aircraft (which is proportional to the average flux, or flow rate, of such aircraft through the milieu of target aircraft). Actually, each type of aircraft can be thought of as serving as a potential collision victim for aircraft of the other type as well as a collision threat against aircraft of the other type. Although aircrews and air traffic specialists strive to keep all aircraft separated, increasing the flight hour rate of aircraft type X or of aircraft type Y or both, or waiting longer, will present more opportunities for collision between aircraft of types X and Y. For forecasting purposes, each unit of time (year) and flight hour rate (100,000 hours per year) for each type of aircraft is treated as a Bernoulli trial—one of many statistically identical situations which have the same probability of a collision. This is an approximation, but a good one.

MACs are so rare that there were no collisions of types P-O (and O-P), P-P, C-O (and O-C), P-C (and C-P), and C-C during the period 1994-1997. However, the fact that the observed collision rates for these types were zero during this period does not imply that the **probabilities** of collisions of those types were zero. Just as the reports of near-midairs suggest that some risk is indeed present, the mathematics support a consistent conclusion. There is a range of probabilities that would be consistent with the data observed to date. This range reflects the uncertainty in estimation, and we express a confidence interval reflecting a desired level, such as 90 percent confidence. We can state that there is 90 percent statistical confidence that the probabilities were no greater than the upper confidence limits in the rightmost column of table 3-2 above. (That is, the rate could be any value between this limit and zero.) Of the collision types with no collisions during 1994-1997, the upper confidence limit is greater for those types with less exposure as measured by the flight hour rate product—i.e., with less opportunity to measure the actual collision probability. Because type C aircraft flew fewer hours per year than did type P and type O aircraft, there is more uncertainty about the probability of a type C-C collision per year per (million flight hours per year)^2 than about other collision types. The upper 90 percent confidence limit is more than 20 times that for O-O collisions; although there were 61 O-O MACs during the four year period, type O aircraft flew enough flight hours to provide 90 percent statistical confidence that the collision probability per year per (100,000 flight hours per year)^2 is no greater than 0.0009. These ranges of uncertainty are shown graphically in Figure 3.2.

We stress that the higher confidence limit given for Cargo-Cargo pairs does not indicate a higher rate for that class; only that there is a wide uncertainty regarding this probability, relative to the other pair classes.

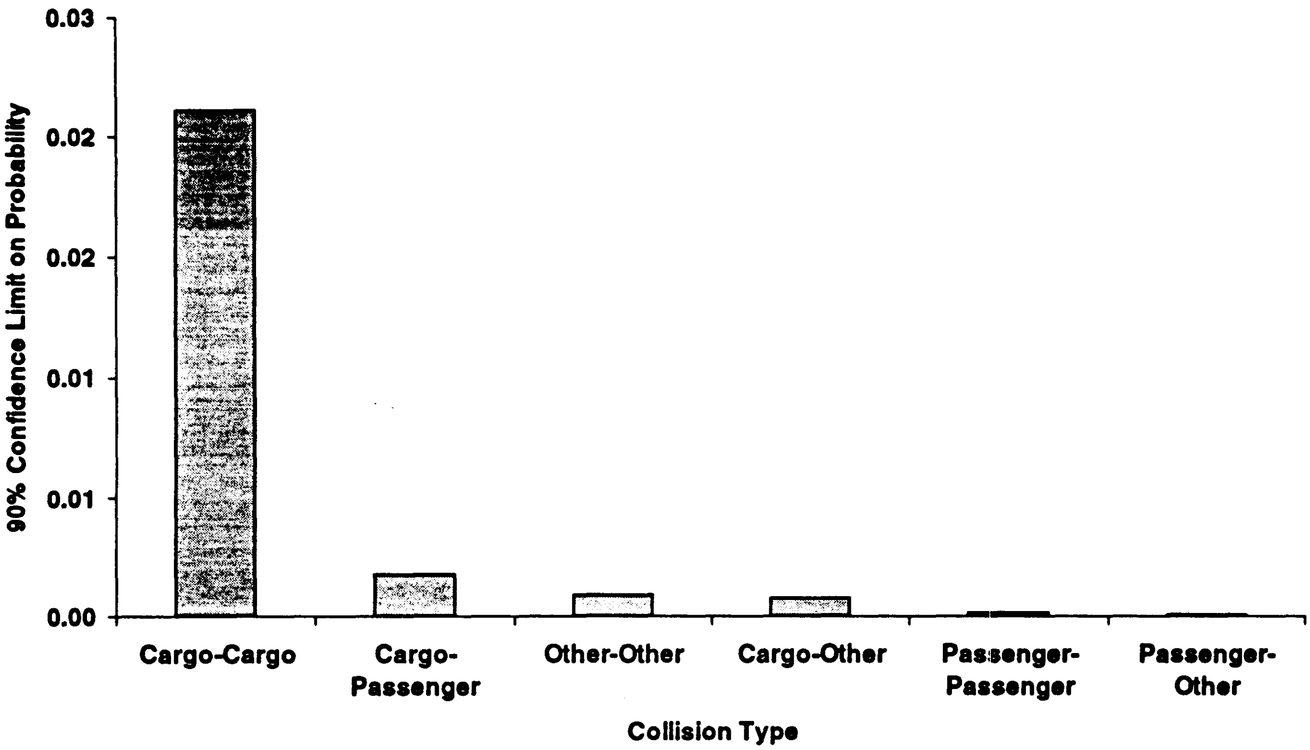

Figure 3.2. Upper 90 percent Confidence Limits on Collision Probabilities per Year per (100,000 Flight Hours per Year) per (100,000 Flight Hours per Year)

For predicting the collision risk of cargo carriers, it should be noted that their operations are concentrated at hub airports. Several of the biggest hubs are located at Louisville KY, Memphis TN, and Wilmington OH. The carriers also operate secondary hubs in places such as Miami and the Los Angeles area, and have operations extending to large numbers of major airports. Since NMAC reports for passenger carriers frequently identify conflicts between these and small aircraft, it can be assumed that the cargo carriers would experience similar risk situations in both en route and terminal operations.

The extent to which cargo carriers interact with other types of aircraft is studied quantitatively in Section 4 of this report.

3.3 Growth in Collision Risk

If the annual collision rates (or probabilities) per flight hour rate product remain as they were in 1994-1997, the number of collisions would be projected to increase, because annual flight hour rates are forecast to increase--at different rates for each type of operation. We have estimated the probabilities of different possible numbers of collisions of each type in 2010 assuming that (1) annual type P flight hours grow relative to 1997 at the rate forecast by the FAA for U.S. commercial air carrier airborne hours,[xi] (2) annual type O flight hours grow at the rate forecast for U.S. general aviation and air taxi operations,[xii] and (3) annual type C flight hours grow at the rate forecast for combined domestic freight/express revenue ton miles (RTMs) and domestic mail RTMs.[xiii] The growth factors are 1.23, 1.24, and 1.94, respectively, resulting in the growth, shown in Figure 3.3.

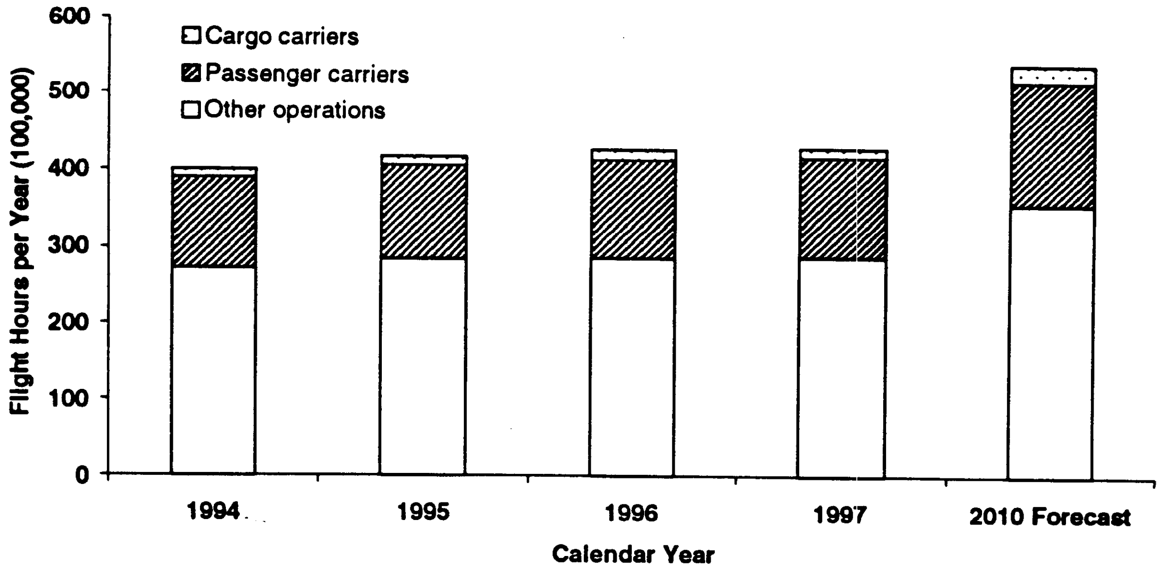

Figure 3.3. Forecast Flight Hours in 2010 Compared to Historical Flight Hours

The key assumptions used in this forecasting method are:

1. The collision risk per flight-hours squared remains a constant rate (thus, increased flying would lead to more collisions proportionally to the growth of this product).
2. No further safety improvements that might reduce collisions will be introduced.

Figure 3.4 shows probabilities of numbers of collisions other than O-O in 2010, assuming that the probability of one collision (of each type) per year per annual flight hour rate product equals the upper 90 percent confidence limits tabulated in Table 3-2. This is a conservative assumption.[xiv]

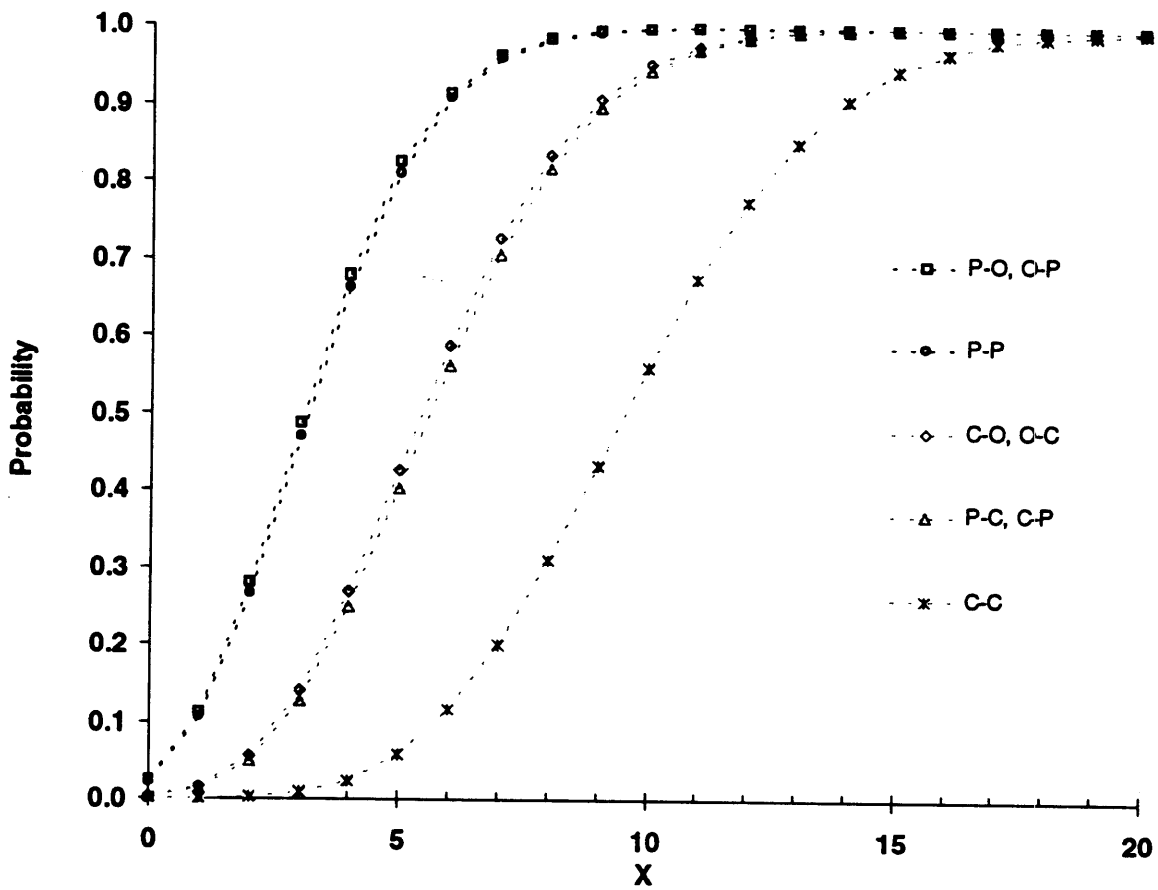

Figure 3.4. Confidence Limits on Probabilities of MACs (Except O-O) in 2010

3.4 Summary

There have been no midair collisions since 1982 involving cargo aircraft of kinds that the proposed rule would affect. However, since 1993 such aircraft have flown so few hours that there is relatively large uncertainty about the underlying probability per year of a midair collision between two cargo aircraft, or between a cargo aircraft and an aircraft of another type.

3.5 Endnotes

[ix] BTS, "Bureau of Transportation Statistics (BTS) Aviation Activity Data (Domestic and International Operations)," http://nasdac.faa.gov/bts/btsfrm41.htm . 14 CFR 241.25 requires each large U.S. air carrier that holds a 401 certificate and operates aircraft designed with a maximum capacity of more than 60 seats or a maximum payload capacity of more than 18,000 pounds to file Form 41 schedules. A domestic carrier that conducts all of its operations under section 418 of the FAA Act (all-cargo certificates) does not file. Foreign air carriers are required to report data, including flight hours, on certain passenger, cargo, and passenger/cargo operations monthly on BTS Form 41 Schedule T-100(f).

[x] FAA, November 15, 1998, *Aviation System Indicators*, http://nasdac.faa.gov/safety_analysis/si.htm .

[xi] FAA/APO-110, March 1999, *FAA Aerospace Forecast--Fiscal Years 1999-2010*, FAA APO-99-1, table 18.

[xii] FAA/APO-110, March 1999, *FAA Aerospace Forecast--Fiscal Years 1999-2010*, FAA APO-99-1, table 24.

[xiii] FAA/APO-110, March 1999, *FAA Aerospace Forecast--Fiscal Years 1999-2010*, FAA APO-99-1, table 16.

[xiv] An alternative assumption is that the probability of one collision (of each type) per year per annual flight hour rate product equals the annual collision rate per annual flight hour rate product observed from 1994 to 1997 and tabulated in table _ above. This is the maximum likelihood estimate of the probability and equals zero for all collision types except O-O.

Section 4

Estimate of Risk Reduction for Cargo Carriers Using TCAS II

4.1 Introduction

The purpose of this study is to estimate the safety improvements that could be expected if "large" cargo aircraft (aircraft with a maximum take-off weight of 15,000 kg or more) were equipped with TCAS II. The assessment focuses on the risk of a MAC between a cargo aircraft and another aircraft. The final estimates, which are given in the form of risk ratios, separate between the cases in which the other aircraft is a passenger aircraft, another cargo aircraft, and a GA aircraft. The estimates are obtained by combining rough estimates of the level of exposure characterizing each case with the NMACs risk reduction estimates documented in the Safety Analysis of TCAS Version 7 [1], which generically apply to any "large" transport category aircraft.

The estimates derived in this report depend on a number of simplifying assumptions, which are believed to be consistent with the level of accuracy that can be achieved when estimating the probabilities of such rare events as midair or NMACs. These include the following two major assumptions. First, exposure to a possible midair or NMAC is assumed to be approximately proportional to the number of aircraft pairs flying through the same airspace at about the same time. Third, the NMAC risk reduction estimates documented in the Safety Analysis of TCAS II Version 7, which were derived from aircraft track data collected at major terminal areas for passenger flights, also apply to cargo aircraft.

It should also be noted that this study takes credit only for the Resolution Advisory function of TCAS II. It does not take any benefit for its Traffic Advisory function, which has been reported by many pilots to be extremely helpful to acquiring and maintaining a greater level of situational awareness. Similarly, this study does not evaluate any benefit that might result from TCAS I, which only provides Traffic Advisories, nor from any alternative collision avoidance technologies.

The results of the analysis are provided in the form of risk ratios or risk reduction factors. This approach is consistent with that adopted in the successive safety analyses of TCAS II and avoids, at least in a first step, the difficulty of deriving a statistical model of MAC rates. A risk ratio corresponds to a relative measure of risk. When referring to the safety implications of TCAS-equipage, a risk ratio indicates the fraction by which the risk of a NMAC is expected to be reduced when the Resolution Advisories provided by TCAS II are correctly followed. Technically speaking, the risk ratios derived in this study, as well as in the successive safety analyses of TCAS II, refer to the risk of a NMAC, as opposed to the risk of a MAC. This choice simply acknowledges the fact that most of the statistical models used in studying the safety of TCAS II were derived from close encounter data and NMAC data, not from MAC data. However, it has been a common practice to treat these risk ratios as providing a strong indication of the expected reduction in the MAC risk. While from a statistical point of view, the relationship between NMAC rates and MAC rates has never been formally established, common sense dictates that a reduction in the former should roughly translate into a proportionately similar reduction in the latter.

4.2 Study Method

The time and budget allocated to this analysis would not have supported an extensive effort of radar data collection and reduction as was done in support of the successive safety analyses of TCAS II. Instead, this analysis is based on estimating the relative exposure to the MAC risk of cargo and passenger flights from the numbers of terminal area operations associated with these flights. Specifically, electronic files of Enhanced Traffic Management System (ETMS) data were obtained, searched, and the number of cargo, GA, and passenger flights that departed from and arrived at selected terminal areas during two-hour time slots were counted. The nature of a flight was identified via the airline identifier in the call-sign. The terminal areas covered by the analysis were chosen carefully so as to include major cargo hubs, major passenger hubs, as well as a few terminal areas with mixed operations. Major satellite airports located within the boundaries of these terminal areas were included in the analysis in order to adequately capture the actual traffic mix.

Since MACs are events taking place between two aircraft, flights departing from and arriving at the selected terminal areas during two-hour time slots were paired. The number of cargo-cargo, cargo-passenger, and cargo-GA pairs were counted. Relative exposure factors in the form of pair probabilities were then computed from these counts of aircraft pairs. This step required yet another simplifying assumption. Specifically, it was assumed that the risk of a NMAC between a pair of aircraft of a given composition is approximately proportional to the total number of such pairs of aircraft present in the same airspace at approximately the same time.

Having obtained relative pair probabilities, it is a simple matter to multiply these probabilities by the risk ratios documented in the Safety Analysis of TCAS II Version 7 in order to obtain estimates of the NMAC risk reduction that a cargo or a passenger flight would experience if cargo aircraft were to equip with TCAS II.

4.2.1 Classes of Aircraft

For simplicity, the study partitions the aircraft population into three classes only:

Cargo Flight

Cargo flights were identified via the airline identifier in the call sign. The set of cargo carriers identified in this study and their identifier are shown in Table 4-1. This method of identifying cargo flights has two obvious limitations. First, cargo flights operated by passenger airlines such as United Airlines, Northwest Airlines, Lufthansa, and others, as well as cargo flights operated by small cargo carriers which are not included in the list will not be counted. Second, no differentiation was made between cargo aircraft that might be subject to a possible mandate to equip with TCAS II and cargo aircraft that would not be subject to the mandate. In this study, all identified cargo aircraft are assumed to be candidate for TCAS II equipage. This simplifying assumption may result in a possible over-estimation of the benefits of equipping cargo aircraft with TCAS II; however, this possibility should be mitigated by the undercounting of cargo flights resulting from the method used for identifying such flights, as well as by the undercounting of GA flights inherent to the approach taken for identifying and counting flights.

GA Flight

GA flights are identified as flights with a call sign consisting of the letter N followed by numerals. In this case, the approach taken has a major limitation in that it cannot capture GA flights operating under (VFR), nor GA flights operating to and from the many small GA airports that are not identified in the list of airports covered by the analysis.

Passenger Flight

Flights not identified as cargo or GA flights were deemed to be passenger flights. Thus, the number of these flights were overcounted, since the count included some military flights, some cargo flights not identified as such, as well as some GA flight not identified as such. In this case, the amount of overcounting should have a relatively small impact on the analysis since the total number of passenger flights in any case dominates the total number of cargo and GA flights by a wide margin.

This study did not account for the part of the passenger airline population carrying 10 to 30 seats and equipped with TCAS I. If TCAS I is less effective than TCAS II (due to the lack of a Resolution Advisory capability of TCAS I), then the amount of risk reduction currently experienced by passenger flights as a result of the TCAS Rule would be slightly overstated. At the same time, this simplification would result in underestimating the benefits of equipping cargo aircraft with TCAS, since some of their potential close encounters with passenger aircraft would be with aircraft that are not equipped with TCAS II.

The study also did not account for any part of the cargo aircraft population that would use aircraft small enough to be exempt from equipping with TCAS. In a like manner, the effectiveness of TCAS for the cargo fleet also may be slightly overstated.

Table 4-1. List of Cargo Carrier

Cargo Carrier	Identifier
Airborne Express	ABX
Air Transport International	ATN
American International Airways	CKS
Atlas Air	GTI
Cargolux Airlines International	CLX
Challenge Air Cargo	CWC
DHL Airways	DHL
Emery Worldwide	EWW
Evergreen International Airlines	EIA
Federal Express	FDX
Fine Airlines	FBF
Nippon Cargo Airlines	NCA
Polar Air Cargo	PAC
Ryan International Airlines	RYN
Southern Air Transport[2]	SJM
United Parcel Service	UPS
Volga-Dnepr Airlines	VDA

[2] This cargo carrier has apparently ceased operations. This fact was not known at the time the data processing was performed. However, this carrier was found to be the only one that did not perform one departure or arrival operation during the selected week.

4.2.2 Terminal Areas Studied

The study samples terminal areas that exhibit significant activity among cargo carriers, and which represent some diversity among other traffic types. Many of the sampled areas are major passenger terminals, and some include major areas of GA activity.

The 14 sites sampled provide coverage of 12 of the 15 top airports for air cargo, including the 3 largest cargo hubs (Memphis, Louisville, and Wilmington OH). Several of the sites also represent international hubs and/or hubs of major passenger carriers (Newark, Philadelphia, Chicago, Atlanta, Los Angeles). The two "smallest" cargo airports studied were chosen to explore interactions with other traffic types (Ontario, Indianapolis). We believe that this collection of sites accounts for a large portion of the nation's cargo traffic, but a lesser fraction of passenger traffic. While only a small portion of the GA traffic is included, it should account for a relatively large portion of the GA traffic most susceptible of being potentially involved in a close encounter with a TCAS-equipped aircraft.

At each site, all major satellite airports covered by the Terminal Radar Approach Control (TRACON) were included to give proper treatment to traffic (especially GA traffic) that shared airspace with the major airport. (An exception was made for the New York TRACON, since it covers a broad area encompassing three major terminals. In this case, only secondary airports in New Jersey and upstate New York were included with traffic for Newark.) Appendix A lists the secondary airports considered for each site.

The following airports, ranked by decreasing order of cargo volume, were used in the study (table 4-2). Note that Dayton/Wilmington and Oakland/San Francisco are combined, since they are covered by common TRACONs, and are considered to share airspace.

Table 4-2. List of Terminal Areas

Airport	Cargo Hub	Major Passenger Hub	International Gateway
Memphis	X		
Los Angeles			X
Louisville	X		
Chicago		X	X
Newark		X	X
Atlanta		X	
Dallas/Ft Worth	X	X	
Dayton/Wilmington	X		
San Francisco/Oakland	X	X	X
Indianapolis	X		
Philadelphia	X		
Ontario	X		
Minneapolis/St Paul		X	
Charlotte			

4.3 Data Analysis

Previous TCAS II Safety Studies have estimated the relative risk of collision between two aircraft in conflict (i.e., in close proximity and converging) when one or both of them are

TCAS-equipped as compared to the case in which neither is TCAS-equipped. To extend the risk calculation to a given population of aircraft, as opposed to one generic pair of aircraft, the probabilities that a pair of aircraft in conflict involve one aircraft in the target population and another aircraft from another population (or two aircraft in the target population) need to be evaluated. For this purpose, data on aircraft flying in the same airspace at about the same time needed to be obtained. These data were extracted from files of ETMS data recorded by the host computer.

Files of recorded ETMS data were available at MITRE Center for Advanced Aviation System Development (CAASD). These files contain messages from the host computer concerning flights over the continental U.S. Each one contains one full day of data (24 hours), which include, in particular, departure and arrival messages for all flights controlled by ATC.

Departure and arrival messages contain eight fields of information, including the time stamp of the message, the type of message, the call-sign of the flight, the aircraft type, the airport of departure, the airport of arrival, the time of departure, and either the expected time of arrival or the actual time of arrival, depending on the message type.

Arrival and departure messages were extracted for one full week of operation extending from Monday, 17 May to Sunday, 23 May 1999. These messages were sorted according to the category of the flight (cargo, GA, and passenger, as defined previously), the airport or arrival (for arrival messages) or the airport of departure (for departure messages), and the time stamp of the message. The number of these messages were then counted for each airspace of interest, each flight category, and each two-hour period.

For example, the numbers of arrivals and departures shown in Table 4-3 were obtained for the Atlanta terminal airspace for the selected week.

Table 4-3. Operation Counts for the Atlanta Airspace

Time Slot (GMT)	cargo arrival	cargo departure	GA arrival	GA departure	passenger arrival	passenger departure
0:00 - 1:59	3	1	110	75	934	880
2:00 - 3:59	11	67	61	37	655	862
4:00 - 5:59	2	23	17	8	107	156
6:00 - 7:59	8	0	6	6	42	40
8:00 - 9:59	45	4	8	13	121	29
10:00 - 11:59	20	5	40	153	564	423
12:00 - 13:59	10	7	189	234	896	899
14:00 - 15:59	1	10	185	164	771	761
16:00 - 17:59	2	2	147	174	845	1036
18:00 - 19:59	14	1	236	241	1011	789
20:00 - 21:59	5	1	269	253	999	912
22:00 - 23:59	6	6	213	134	855	866

From these data, the number of different pairs of aircraft that can be formed for each time slot can easily be computed. First, since for this purpose there is no significant difference between an arrival and a departure, one can sum them up for each category of flight to obtain numbers of operations. Then, the number of pairs involving aircraft from the same population (e.g., cargo/cargo) can be calculated using the formula:

$$N_{i,i} = \frac{n_i(n_i - 1)}{2}$$

where $N_{i,i}$ is the number of pairs and n_i is the number of operation for category of flight i.

- The number of pairs involving aircraft from different populations (e.g., cargo/passenger) can be calculated using the formula:

$$N_{i,j} = n_i n_j$$

where $N_{i,j}$ is the number of pairs and n_i (n_j) is the number of operation for category of flight i (j). Note that in these computations, the order of the aircraft in the pair does not matter.

Carrying these computations yields the pair counts shown in Table 4-4 for the first time slot (0:00 - 1:59) at Atlanta.

Table 4-4. Example 2-Hour Pair Counts for the Atlanta Airspace

cargo/GA	740
cargo/passenger	7,256
GA/passenger	335,590
cargo/cargo	6
GA/GA	17,020
passenger/passenger	1,644,391
total pairs	2,005,003

Adding the results obtained for the 12 successive time slots gives the total accumulated pair counts shown in Table 4-5 for the selected week at Atlanta.

Table 4-5. Hour Pair Counts for the Atlanta Airspace

cargo/GA	41,724
cargo/passenger	278,847
GA/passenger	5,036,539
cargo/cargo	5,196
GA/GA	551,754
passenger/passenger	12,804,983
total pairs	18,719,043

Pair probabilities are obtained by dividing the number of pairs of each kind by the total number of pairs, which, for the Atlanta airspace, yields the results shown in Table 4-6.

Table 4-6. Pair Probabilities for the Atlanta Airspace

cargo/GA	0.0022
cargo/passenger	0.0149
GA/passenger	0.2691
cargo/cargo	0.0003
GA/GA	0.0295
passenger/passenger	0.6841
total pairs	1.0000

This analysis was repeated for each of the selected airspaces. The pair probabilities computed for the various airspaces were then be summed up, in a weighted sum that takes the respective numbers of operations into account, to obtain pair probabilities that apply over the entire set of selected airspaces. These pair probabilities are shown in Table 4-7.

Table 4-7. Pair Probabilities for the Selected Airspaces

cargo/GA	0.023
cargo/passenger	0.068
GA/passenger	0.251
cargo/cargo	0.044
GA/GA	0.042
passenger/passenger	0.573
total pairs	1.000

From these pair probabilities, the conditional pair probabilities shown in Table 4-8 can be computed, where P(cargo/ .) represents a conditional pair probability, given that one aircraft is a cargo flight, and P(passenger/ .) represents a conditional pair probability, given that one aircraft is a passenger flight.

Table 4-8. Conditional Pair Probabilities for the Selected Airspaces

Conditional Probability	Other aircraft		
	cargo	GA	passenger
P(cargo/ .)	0.324	0.174	0.503
P(passenger/ .)	0.076	0.281	0.643

To provide some perspective to these results, the total counts of operations that were obtained for the selected terminal areas and also for all domestic airports found in the ETMS data (for the selected week) are shown in Table 4-9. As Table 4-9 shows, the analysis captures a significant proportion of the total number of dometic terminal area operations.

Table 4-9. Operation Counts for All Domestic Airports

Flight Operations	**Selected Airspaces**	**All Domestic Airports**
cargo arrival	3,922	8,363
cargo departure	3,825	8,955
GA arrival	11,319	63,195
GA departure	11,419	75,854
passenger arrival	54,846	206,654
passenger departure	53,019	254,073

Finally, it is interesting to compare the results obtained individually for each terminal area, particularly when these are graphically presented as in Appendix C. These results confirm the roles played by certain airports as, for example, cargo hubs or passenger hubs, as well as the distribution of the traffic throughout the day, which shows not only a predominance of cargo flights at night and a predominance of passenger flights during the day, but also a non-negligible mix of cargo, passenger, and GA flights throughout the day in many terminal areas. Note that in comparing these charts, it is important to keep in mind that time is referenced to the Greenwich meridian.

4.4 Results and Safety Calculations

The risk calculations rely on the assumption that the risk of NMAC is proportional to the pair probabilities. Accordingly, estimates of the risk reduction that would result from equipping cargo aircraft with TCAS II can be obtained by multiplying the pair probability of each pair of aircraft of interest by the risk reduction factor associated with TCAS II equipage.

The risk reduction factors (risk ratios) for TCAS II (Version 7) were generated for a variety of near-midair encounter collision geometries and the associated probabilities of occurrences derived from aircraft track data recorded at twelve major domestic terminal areas. This analysis assumes that the same mix of encounter geometries would apply to all users of TCAS II, whether they be cargo or passenger aircraft, and thus, that the risk ratios computed for passenger aircraft are also applicable to cargo aircraft. Table 4-10 presents risk ratios are taken from the Safety Study of TCAS II Version 7 [1]. A risk ratio corresponds to a relative risk reduction. In the case of TCAS II, a risk ratio expresses the risk of a NMAC when one or both aircraft are equipped with TCAS relative to the risk of a NMAC when neither aircraft is equipped with TCAS. Since TCAS tracks intruder aircraft using the information provided in their transponder replies, the risk ratios are somewhat dependent on the quality of the altimetry systems on the intruder aircraft.

Table 4-10. TCAS II Risk Ratios

Encounter Type	100-ft altimetry	25-ft altimetry
Non-TCAS vs non-TCAS	1.000	1.000
TCAS vs non-TCAS	0.093	0.076
TCAS vs TCAS	0.023	0.023

In this study, it is assumed that only 5 to 10 percent of aircraft would be equipped with a Mode S transponder and 25-ft altimetry systems. This approach is very conservative since TCAS equipage requires a Mode S transponder, and 25-ft altimetry systems are quite often installed along with the Mode S transponder. With this assumption, the numbers in the two columns of Table 4-10 can be combined into a risk ratio of 0.092 for encounters between on TCAS aircraft and a non-TCAS aircraft and risk ratio of 0.023 for encounters between two TCAS aircraft.

Note that these risk ratios take an encounter between two aircraft that are not TCAS-equipped as reference or baseline case. Thus, to estimate the reduction in risk expected from equipping cargo aircraft with TCAS, one has to first calculate the risk reduction that has already occurred due to the TCAS Rule for passenger aircraft, then calculate the additional risk reduction that would occur if cargo aircraft were to equip with TCAS. Clearly, the cargo and passenger aircraft perspectives will be quite different in this regard since a passenger aircraft is much more likely to be in a close encounter with another passenger aircraft than with a cargo aircraft and its risk has already been substantially decreased by the TCAS it is required to carry.

4.4.1 Cargo Aircraft Perspective

Table 4-11 shows the pair probabilities conditioned on encounters involving at least one cargo aircraft as well as the relevant TCAS risk reduction factors.

Table 4-11. Risk Reduction for Cargo Aircraft

	Cargo / cargo	**Cargo / GA**	**Cargo / passenger**	**Cargo / unspecified**
Conditional pair probability	0.324	0.174	0.503	1.000
Risk when cargo is not TCAS-equipped	1.000	1.000	0.092	0.544
Risk when cargo is TCAS-equipped	0.023	0.092	0.023	0.035

Combining these risks in a weighted manner according to the conditional pair probabilities shown in Table 4-8 and reproduced in the first row of Table 4-11, the risk to cargo aircraft when they are not TCAS-equipped is 0.544 (as compared to the pre-TCAS baseline situation when no aircraft was TCAS-equipped). If cargo aircraft were TCAS-equipped this relative risk would drop to 0.035 (as compared to the pre-TCAS baseline situation when no aircraft was TCAS-equipped). This corresponds to a risk reduction factor of 0.035/0.544 = 0.064 or about 1/15. In other words, cargo aircraft could experience a reduction in their NMAC risk to about one fifteenth (0.035 as compared to 0.0544) of the current risk by installing TCAS II.

4.4.2 Passenger Airline Perspective

For passenger aircraft, that already have TCAS II, the perspective is considerably different, since the cargo aircraft would represent only a small portion of their potential close encounter traffic. Table 4-12 shows the pair probabilities conditioned on encounters involving at least one passenger aircraft.

Table 4-12. Risk Reduction for Passenger Aircraft

	Passenger / cargo	Passenger / GA	Passenger / passenger	Passenger / unspecified
Conditional pair probability	0.076	0.281	0.643	1.000
Risk when cargo is not TCAS-equipped	0.092	0.092	0.023	0.070
Risk when cargo is TCAS-equipped	0.023	0.092	0.023	0.058

Combining these risks in a weighted manner according to the conditional pair probabilities shown in Table 4-8 and reproduced in the first row of Table 4-12, the risk to passenger aircraft when cargo aircraft are not TCAS-equipped is 0.070 (as compared to the pre-TCAS baseline situation when no aircraft was TCAS-equipped). If cargo aircraft were TCAS-equipped this relative risk would drop to 0.058 (as compared to the pre-TCAS baseline situation when no aircraft was TCAS-equipped). This corresponds to a Risk Ratio of 0.058/0.070 = 0.828, which roughly corresponds to a 17 percent reduction compared to the current risk. The small proportion of encounters involving one passenger and one cargo aircraft means that equipping cargo aircraft with TCAS would only reduce the risk to the passenger aircraft by another one percent (as compared to the pre-TCAS baseline situation when no aircraft was TCAS-equipped) beyond the 93 percent already enjoyed through their TCAS equipage.

4.5 Trend

An identical analysis was performed in October 1997 on the basis of ETMS data for the week extending from Monday, 25 August to Sunday, 31 August 1997. Since air traffic is known to vary throughout the year with an increase during the Spring and a decrease during the Fall, it is not clear how meaningful a comparison between the results derived from the May 1999 data and those derived from the August 1997 data would be. Indeed, it would be impossible to decide whether the differences in the results reflect a long term trend or simply a seasonal effect. Redoing the analysis on the basis of August 1998 data would eliminate the issue of a possible seasonal effect. However, this would still leave the issue of the natural variability in the results open. In order to (at least partially) address these issues of trend and variability, the analysis was repeated not only with August 1998 data (week from 24 to 30 August) but also with April 1999 data (week from 12 to 18 April). Comparing the results obtained with the April 1999 data and the May 1999 data should give a rough idea of the natural variability in the results. Comparing the results obtained with the August 1998 data and the August 1997 data and accounting for the natural variability in the results should give a rough idea of a possible long term trend. The results obtained for these four weeks are given in Tables 4-13 to 4-15.

Table 4-13. Trend and Variability of Pair Probabilities

Pair Probabilities	August 1997	August 1998	April 1999	May 1999
Cargo/GA	0.010	0.012	0.010	0.023
Cargo/passenger	0.037	0.049	0.042	0.068
GA/passenger	0.228	0.230	0.238	0.251
Cargo/cargo	0.022	0.025	0.022	0.044
GA/GA	0.028	0.029	0.030	0.042
Passenger/passenger	0.675	0.654	0.658	0.573

Table 4-14. Trend and Variability of Cargo Risk Ratios

Cargo Risk Ratios	August 1997	August 1998	April 1999	May 1999
Cargo is not TCAS-equipped	0.513	0.481	0.483	0.544
Cargo is TCAS-equipped	0.033	0.032	0.032	0.035

Table 4-15. Trend and Variability of Passenger Risk Ratios

Passenger Risk Ratios	August 1997	August 1998	April 1999	May 1999
Cargo is not TCAS-equipped	0.070	0.072	0.072	0.070
Cargo is TCAS-equipped	0.060	0.063	0.062	0.058

Since in all cases, the difference between the August 1997 and August 1998 results is less than the difference between the April and May 1999 results, one cannot conclude, on the basis of the results presented in herein, on any particular long term trend regarding the safety benefits expected from equipping cargo aircraft with TCAS.

4.6 Conclusions

The analysis presented in this report made an attempt at quantifying the safety benefits that could be expected if cargo aircraft were equipped with TCAS II. These safety benefits were expressed in terms of NMAC risk reduction factors. It was estimated that cargo aircraft could experience a reduction in their NMAC risk to about one fifteenth of the current risk by installing TCAS II. It was also estimated that passenger aircraft could experience a further reduction in their NMAC risk of about seventeen percent of their current risk if cargo aircraft were equipped with TCAS II.

In the course of the analysis a few simplifying assumptions had to be made. Some of these tend to cause the results to overstate the benefits expected from equipping cargo aircraft with TCAS II; others tend to act in exactly the opposite direction. Overall, it is believed that the results presented in this report should present a conservative picture of the expected benefits mostly because of the undercounting of GA flights inherent to the approach taken in the analysis.

List of References

Dr. Michael P. McLaughlin, *Safety Study of the Traffic Alert and Collision Avoidance System (TCAS II), Final Version*, MTR97W00032, June 1997, The MITRE Corporation, McLean, VA.

Appendix A

Selected Terminal Area Airspaces

This Appendix lists the satellite airports that were considered part of the airspace about the major terminals used in the study. Airports that were part of the subject airport's TRACON were included as long as they reported an average of 1.5 instrument operations per week, according to 1993 Airport Activity Statistics. Airports with a smaller number of instrument operations were judged to have too few flight plan messages to make a noticable difference in the data analysis. Moreover, such airports may serve non-transponder aircraft that cannot be protected by TCAS.

Each group in Table A-1 lists one or two major airports followed by the secondary airports grouped with it in the airspace.

Table A-1. Selected Terminal Area Airspaces

Dallas-Fort Worth - DFW

- Dallas Addison - ADS
- Dallas Love - DAL
- Dallas Redbird - RBD
- Ft. Worth Meacham - FTW
- Ft. Worth Alliance - AFW

Minneapolis-Saint Paul - MSP

- Minneapolis Crystal - MIC
- Minneapolis Flying Cloud - FCM
- St. Paul - STP

Ontario - ONT

Chino - CNO

El Monte - EMT

La Verne Brackett - POC

Riverside Municipal - RAL

Los Angeles International - LAX

Hawthorne - HHR

Santa Monica - SMO

Torrance Municipal - TOA

Memphis - MEM

Arlington - LHC

Olive Branch - OLV

West Memphis - AWM

Newark – EWR (Note: this airspace was deemed to contain only secondary airports in New Jersey and upstate New York, not in New York City or Long Island.)

Caldwell - CDW

Linden - LDJ

Morristown - MMU

Newburgh/Stewart - SWF

Poughkeepsie - POU

Somerville - N52

Teterboro - TEB

White Plains - HPN

Indianapolis - IND

Bakalar - BAL

Ind. Eagle Creek - I14

Ind. Metropolitan - UMP

Ind. Terry - I52

Ind. Greenwod - HFY

Ind. Mt. Comfort - MQJ

Shelbyville - 3SM

Oakland - OAK

San Francisco - SFO

Hayward - HWD

San Jose - SJC

Philadelphia - PHL

Ambler - N67

Coatesville - 40N

No. Philadelphia - PNE

Pottstown Mun. - N47

Pottstown - N46

Trenton - TTN

Wilmington - ILG

Charlotte - CLT

Albermarle - 6A6

Gastonia - 0A6

Lincolnton - 5N4

Monroe - EQY

Rockhill - 29J

Salisbury - RUQ

Chicago - ORD

Aurora - ARR

C. DuPage - DPA

C. Hammond/C. Lansing - 3HA

C. Midway - MDW

C. Palwaukee - PWK

Crystal Lake/Lake in Hills - 3CK

DeKalb - DKB

Frankfort - C18

Gary - GYY

Griffith - 05C

Joliet - JOT

Lockport - LOT

Naperville - LL10

Plainfield - 1C5

Waukegan - UGN

Atlanta - ATL

A. Dekalb Peachtree - PDK

A. Fulton Co. - FTY

Carrollton W. - CTJ

Covington - 9A1

Griffin - 6A2

Lawrence - LZU

Marietta/Cobb - RYY

Marietta - MGE

Dayton - DAY

Wilmington - ILN

Middletown - MWO

Montgomery Co. - MGY

Richmond - RID

Sidney - I12

Springfield - SGH

Wapakoneta - AXV

Wright Patterson - FFO

Xenia - I19

Louisville - SDF

Jeffersonville - JVY

L. Bowman - LOU

Appendix B

Relationship Between Encounter and Operation Rates

This Appendix examines the hypothesis that close encounters are proportional to the density of aircraft pairs in the airspace. The set of encounters comprising the TCAS Safety Database is used. This data was collected from 12 ARTS sites in 1989-90, prior to the deployment of TCAS. It represents a variety of large terminal areas, including some with heavy GA activity. Fortuitously, there is some overlap with the sites considered in the analysis in the body of this report.

During the development of TCAS Version 7, all of the tracks in this database were resmoothed and reprocessed using an improved credibility test. Some tracks were discarded as being too short to support the TCAS safety study, while others were found to contain non-credible reports. The remaining tracks are of very high confidence.

The number of close encounters that remained were calculated as a rate per hour of data collection. Since each radar collected data from a sizeable airspace, the traffic statistics were examined for both the primary airport and for the major secondary airports controlled by the TRACON. Airport activity levels were taken from FAA Air Traffic Activity, Fiscal Year 1993.

Table B-1 lists the Automated Radar Terminal System (ARTS) sites and the airports that were included in the tabulation of activity level. Table B-2 compares the rate of encounters with the activity levels. Figure B-1 shows a scatter plot of the data along with a linear regression line.

It can be seen that there is a rough correspondence between encounters and pairwise traffic level. It is probable that other factors also are involved. These might include, for example, differences in the time distribution of activity, which could be obscured in annual totals, or by a mix of commercial vs. recreational flying in the airspace.

Table B-1. ARTS Sites

Burbank
- Van Nuys

Coast TRACON
- Fullerton
- Long Beach
- Santa Ana/Orange County

Cincinnati

Denver (Stapleton)
- Broomfield Jefferson Co.
- Centennial

Dallas-Ft. Worth
- Dallas Addison
- Dallas Love
- Dallas Redbird
- Ft. Worth Meacham
- Ft. Worth Alliance

New York - JFK
- Farmingdale
- Islip Macarthur

Laguardia

Los Angeles International

Hawthorne

Santa Monica

Torrance Mun.

Memphis

Minneapolis-St. Paul

Minneapolis Crystal

Minneapolis Flying Cloud

St. Paul

Ontario

Chino

El Monte

La Verne Brackett

Riverside Municipal

Seattle-Tacoma

Olympia

Renton

Boeing

Tacoma Narrows

St. Louis Lambert

Spirit of St. Louis

Table B-2. Encounter Rate as Function of Airspace Density

	Operations per year	Encounters	Hours of Data	Encounters per hour
Cincinnati	306811	9	50.77	0.18
Memphis	337608	68	287.88	0.24
St.Louis	593078	140	135.68	1.03
Burbank	712503	950	142.05	6.69
Ontario	927868	679	160.37	4.23
Minn.-St.P	973855	341	299.57	1.14
Seattle	982230	115	56.08	2.05
NY-JFK	1087293	104	33.75	3.08
Coast	1097939	525	48.40	10.85
Denver	1110528	527	138.23	3.81
LA-Int'l	1242996	528	36.45	14.49
Dallas-Ft.W	1703949	374	46.30	8.08

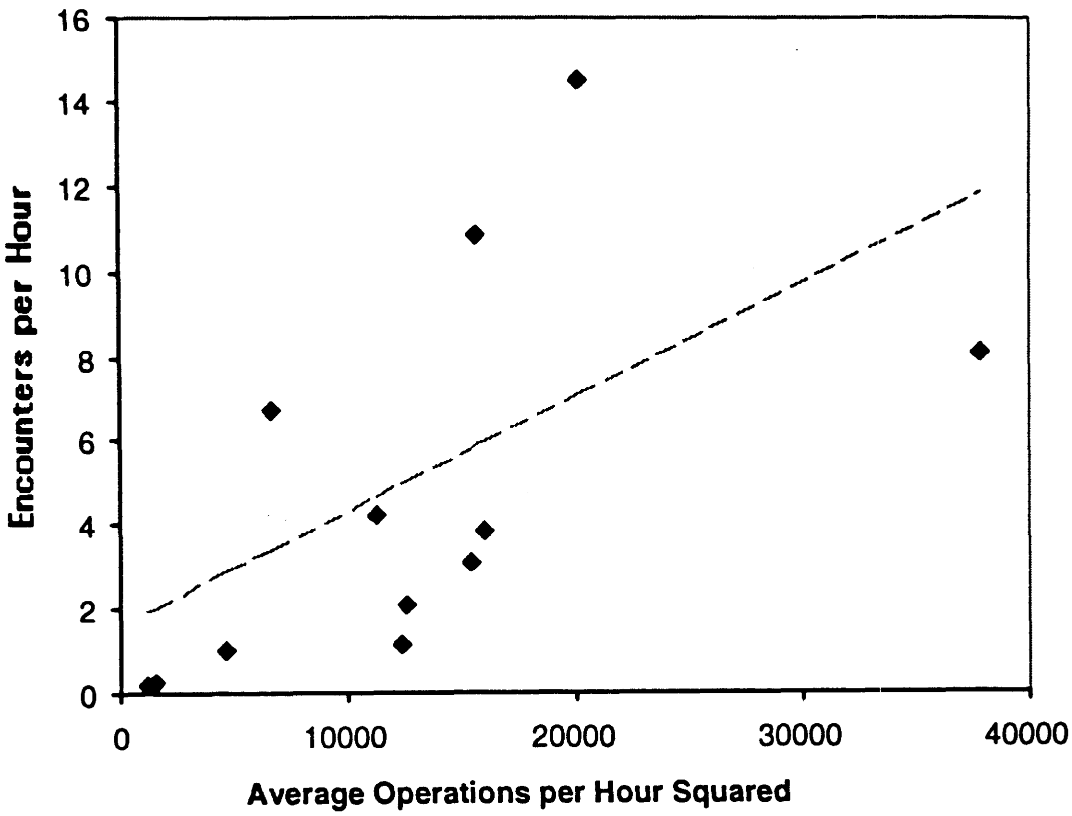

Figure B.1. Encounter vs. Operation Rates

Appendix C

Traffic Distributions for the Selected Airspaces

The following figures show the numbers of arrival and departure operations performed by each of the three flight categories of interest (passenger, cargo, GA) during the week of 17-23 May 1999 at each of the terminal area selected for this study. The operation counts are shown for each 2-hour segment.

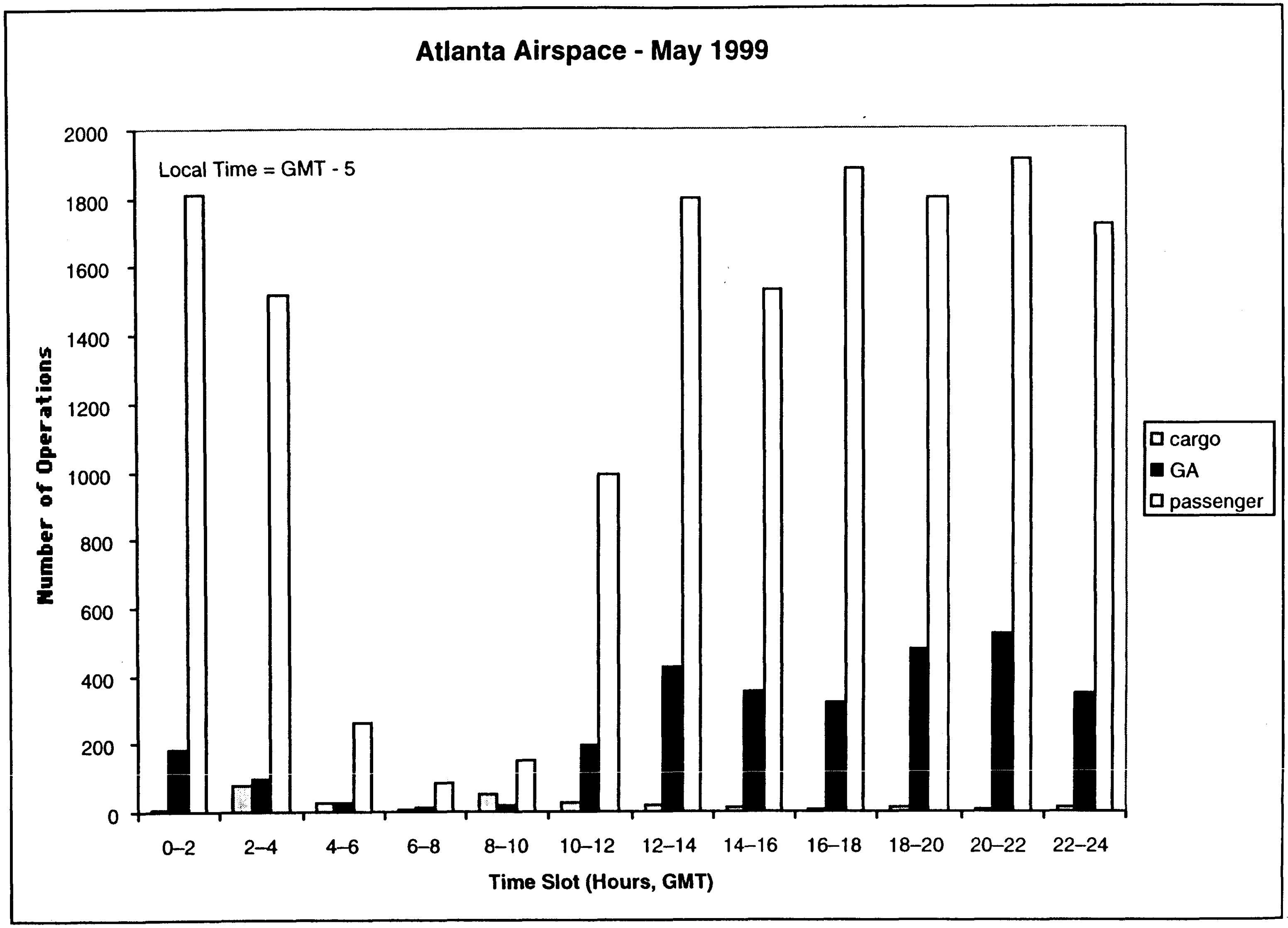

Figure C.1. Atlanta Airspace – May 1999

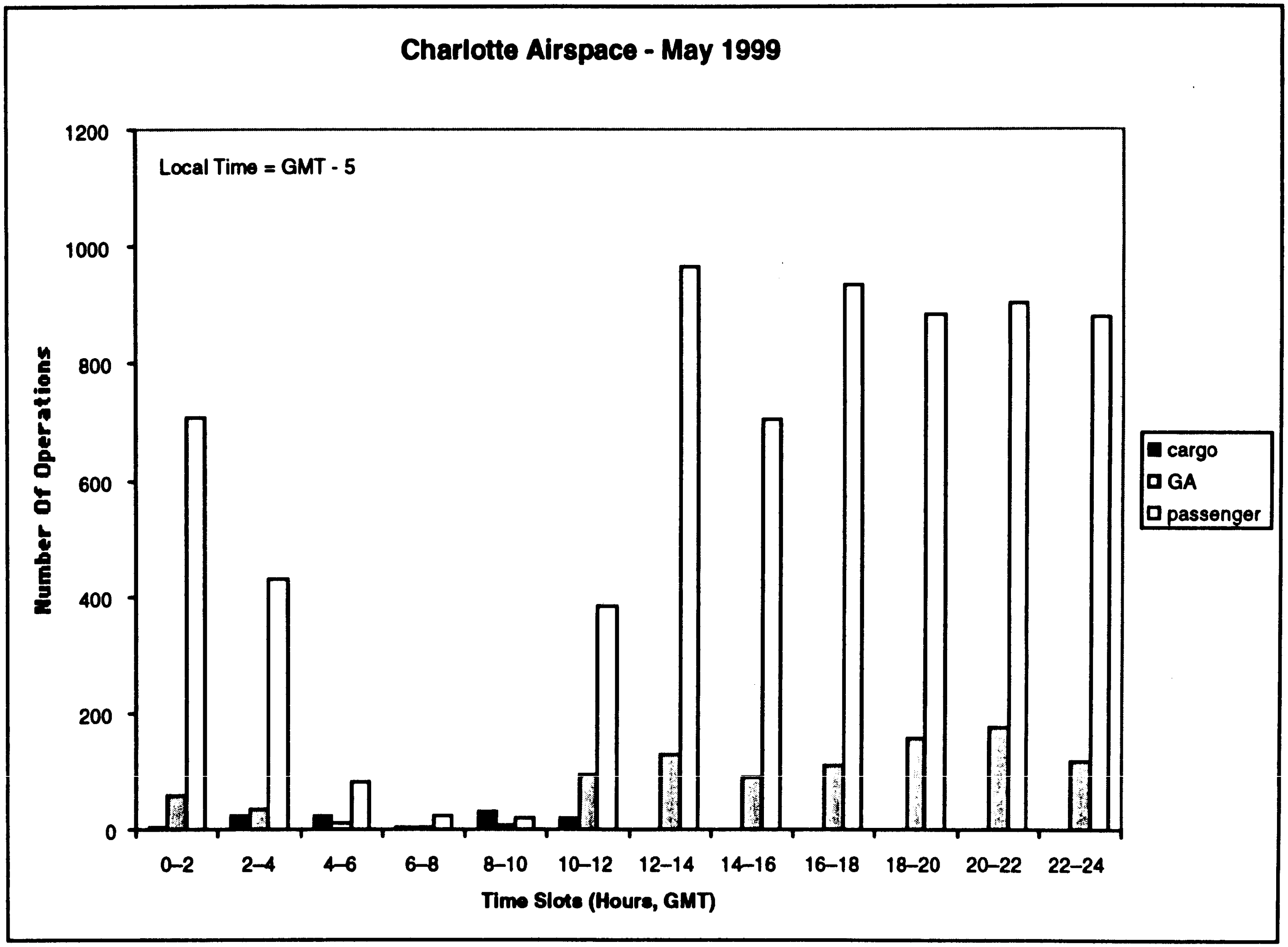

Figure C.2. Charlotte Airspace – May 1999

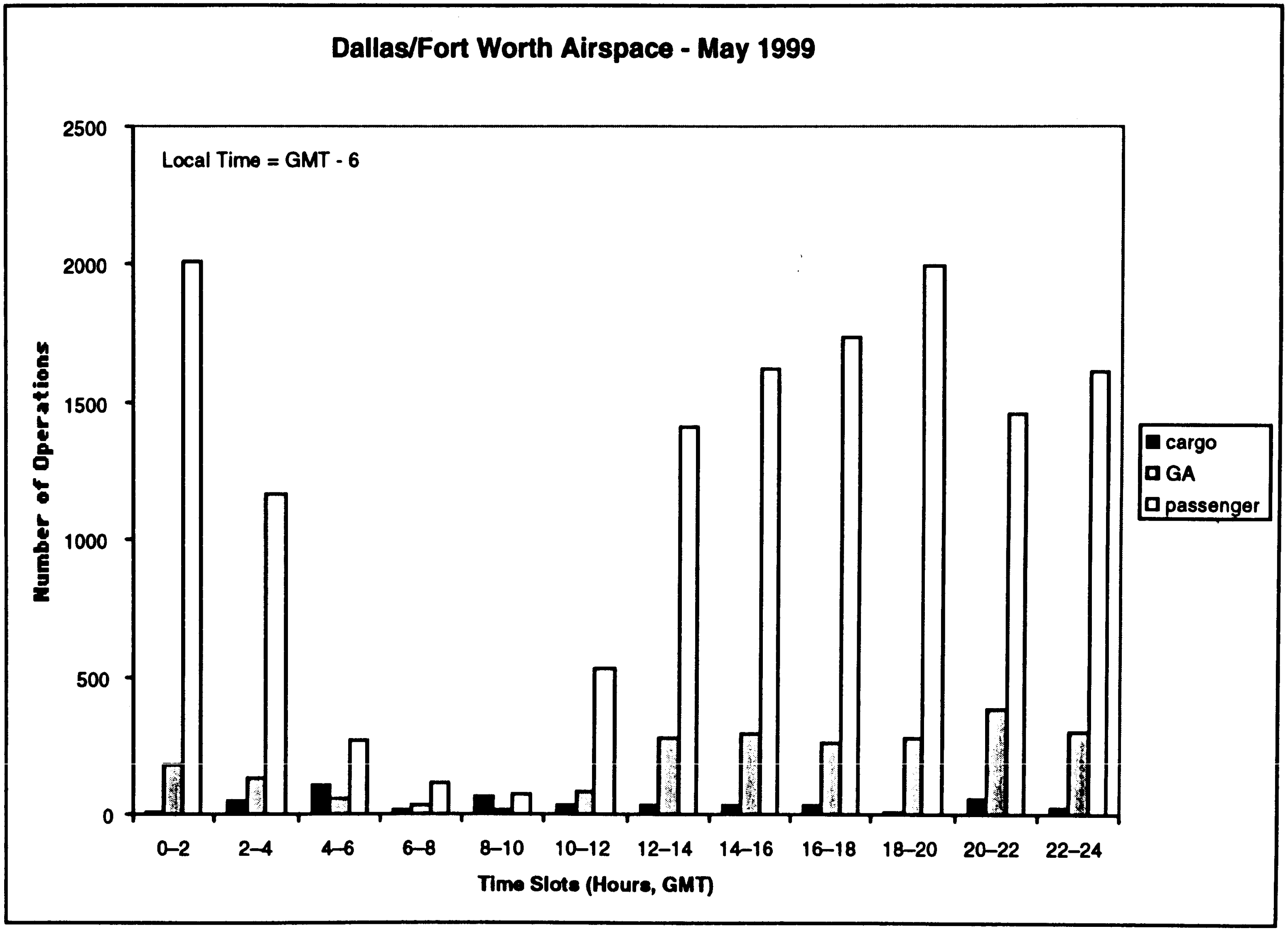

Figure C.3. Dallas/Fort Worth Airspace – May 1999

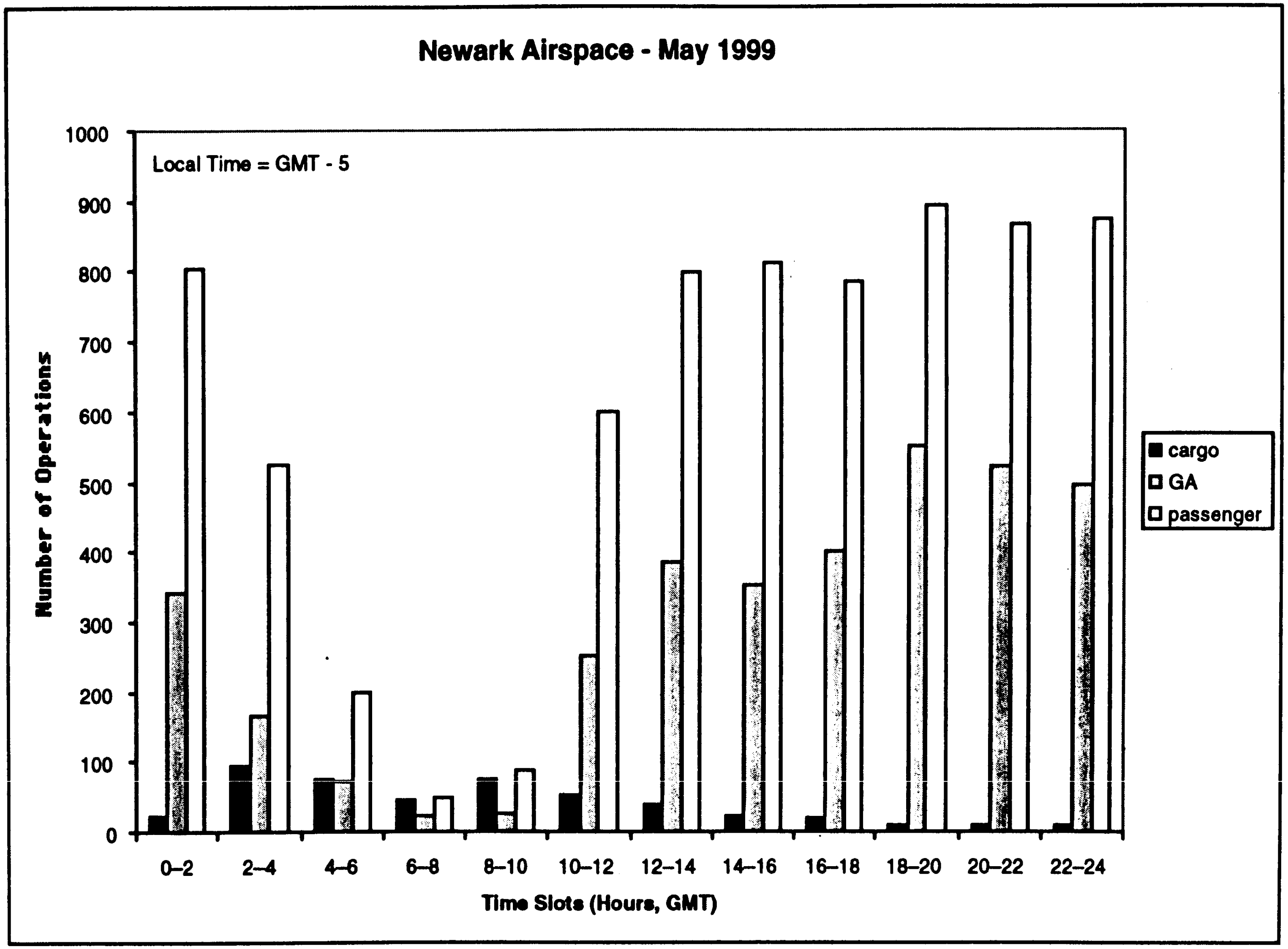

Figure C.4. Newark Airspace – May 1999

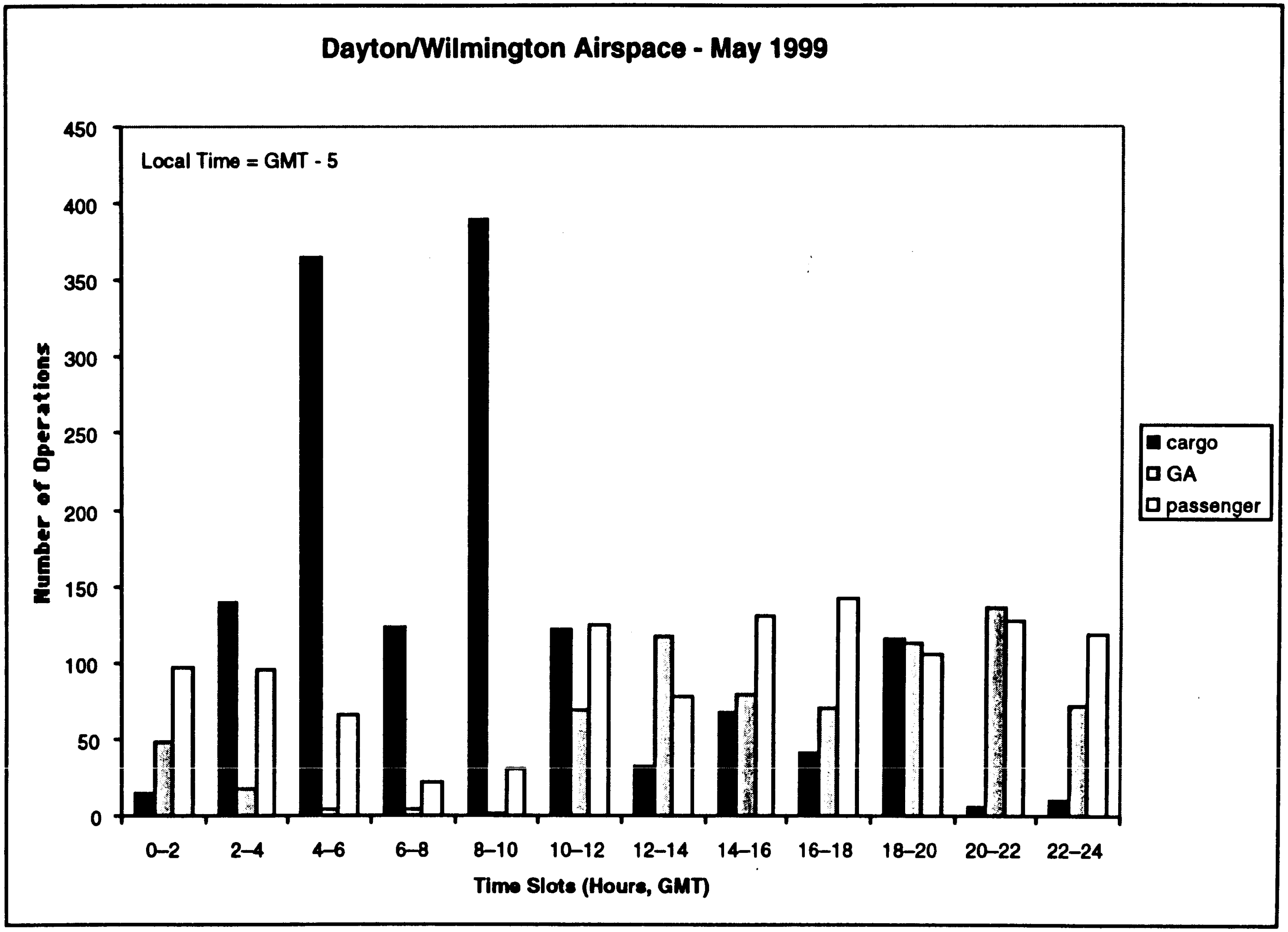

Figure C.5. Dayton/Wilmington Airspace – May 1999

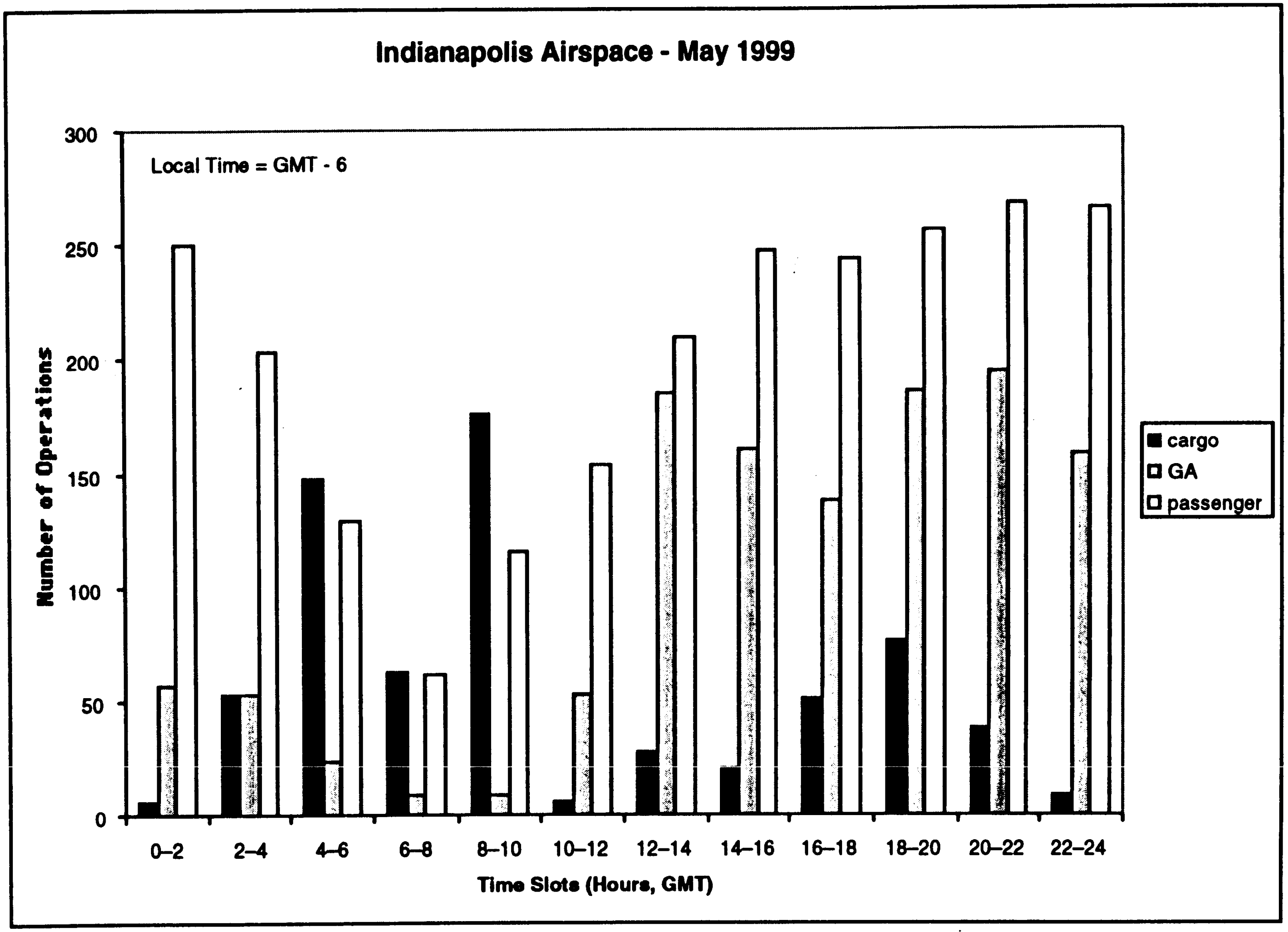

Figure C.6. Indianapolis Airspace – May 1999

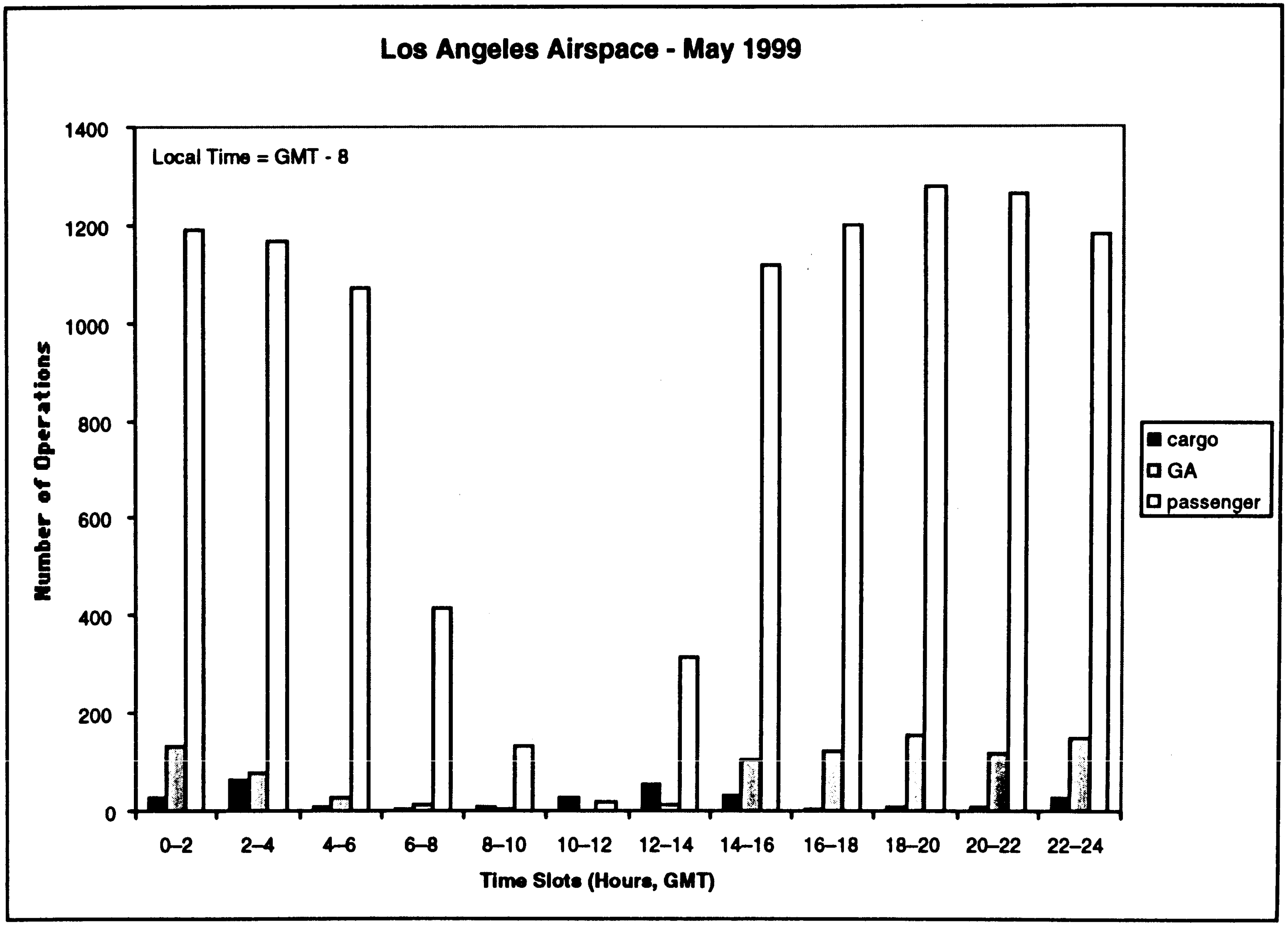

Figure C.7. Los Angeles Airspace – May 1999

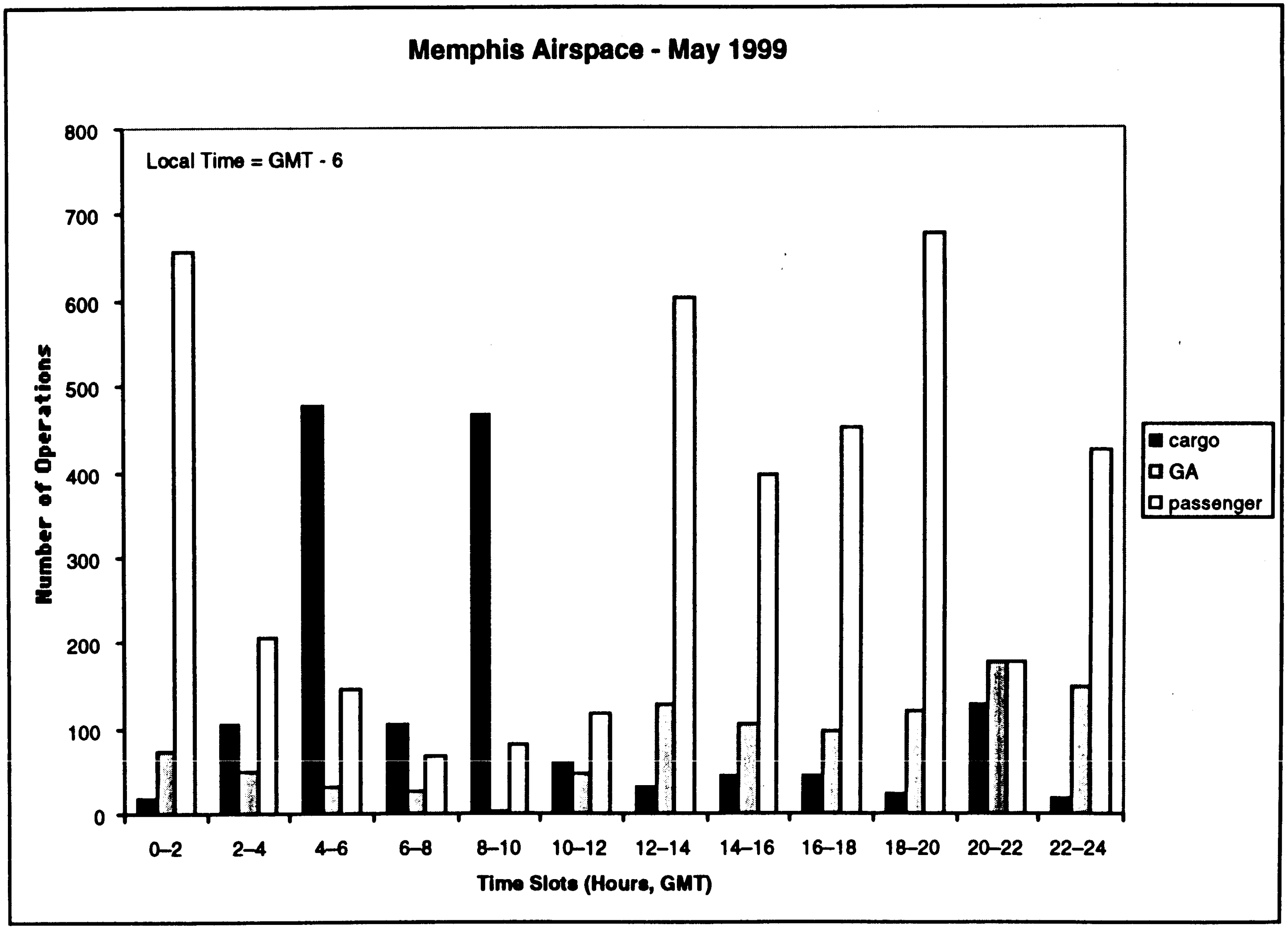

Figure C.8. Memphis Airspace – May 1999

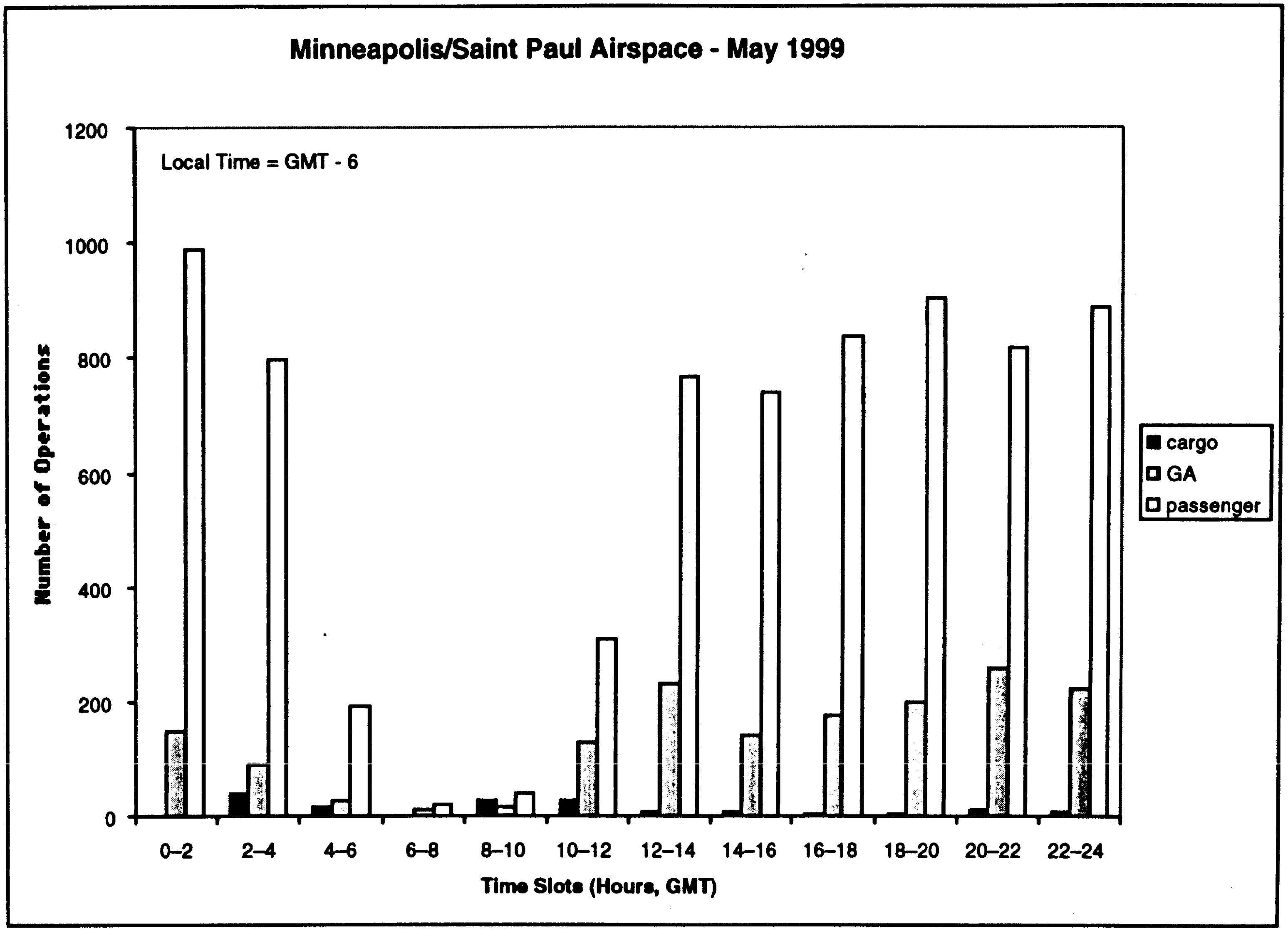

Figure C.9. Minneapolis/Saint Paul Airspace – May 1999

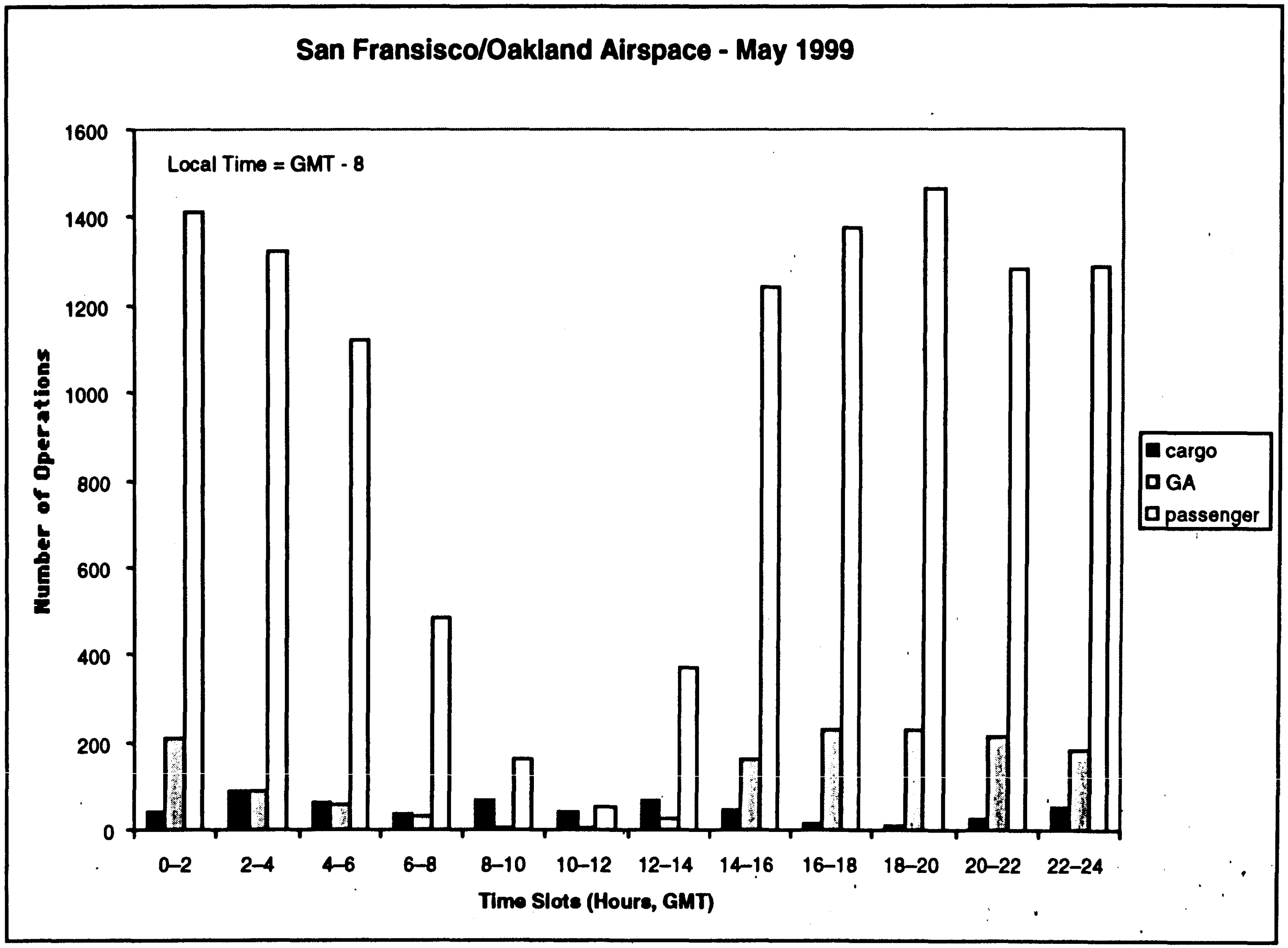

Figure C.10. San Francisco/Oakland Airspace – May 1999

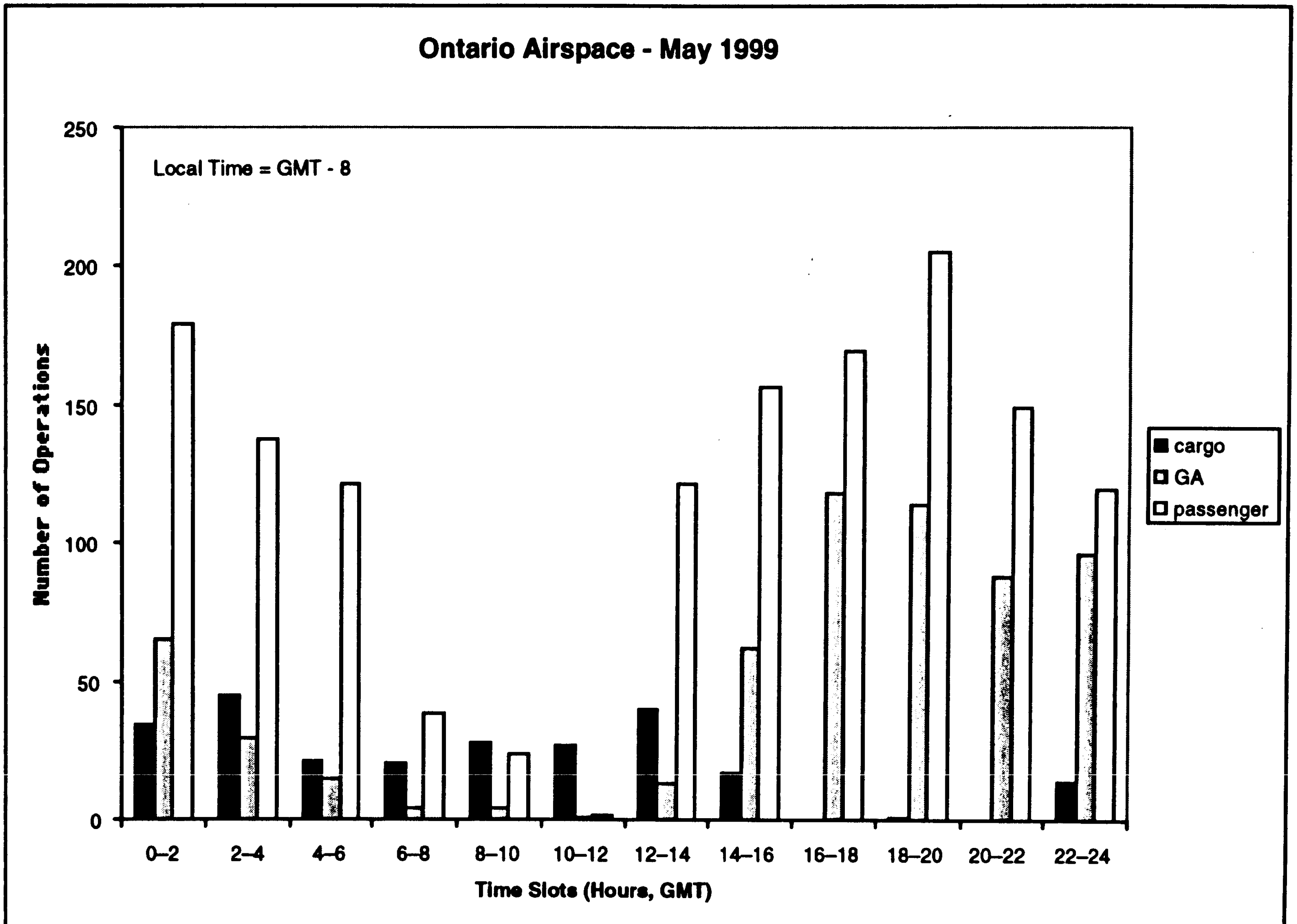

Figure C.11. Ontario Airspace – May 1999

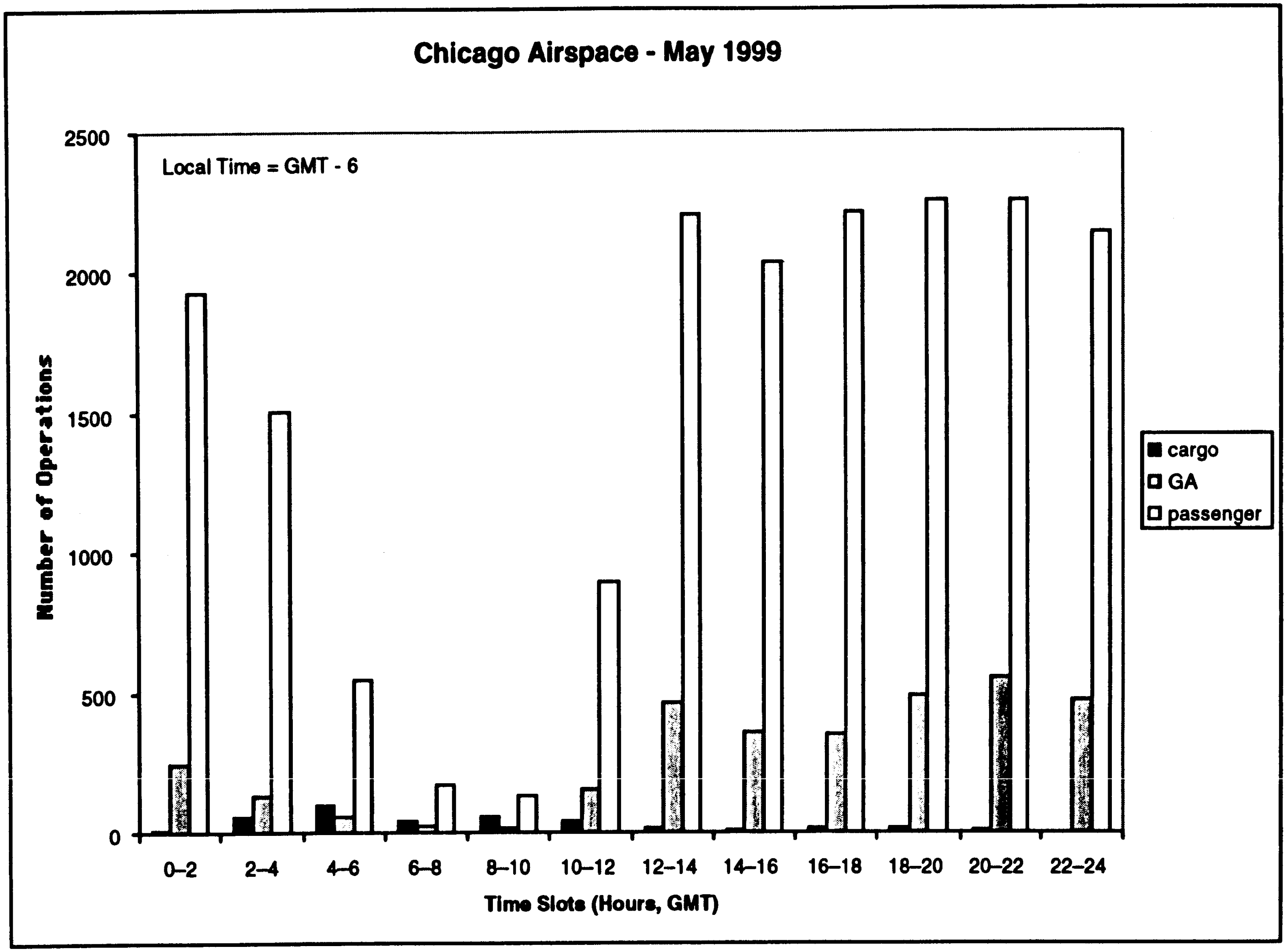

Figure C.12. Chicago Airspace – May 1999

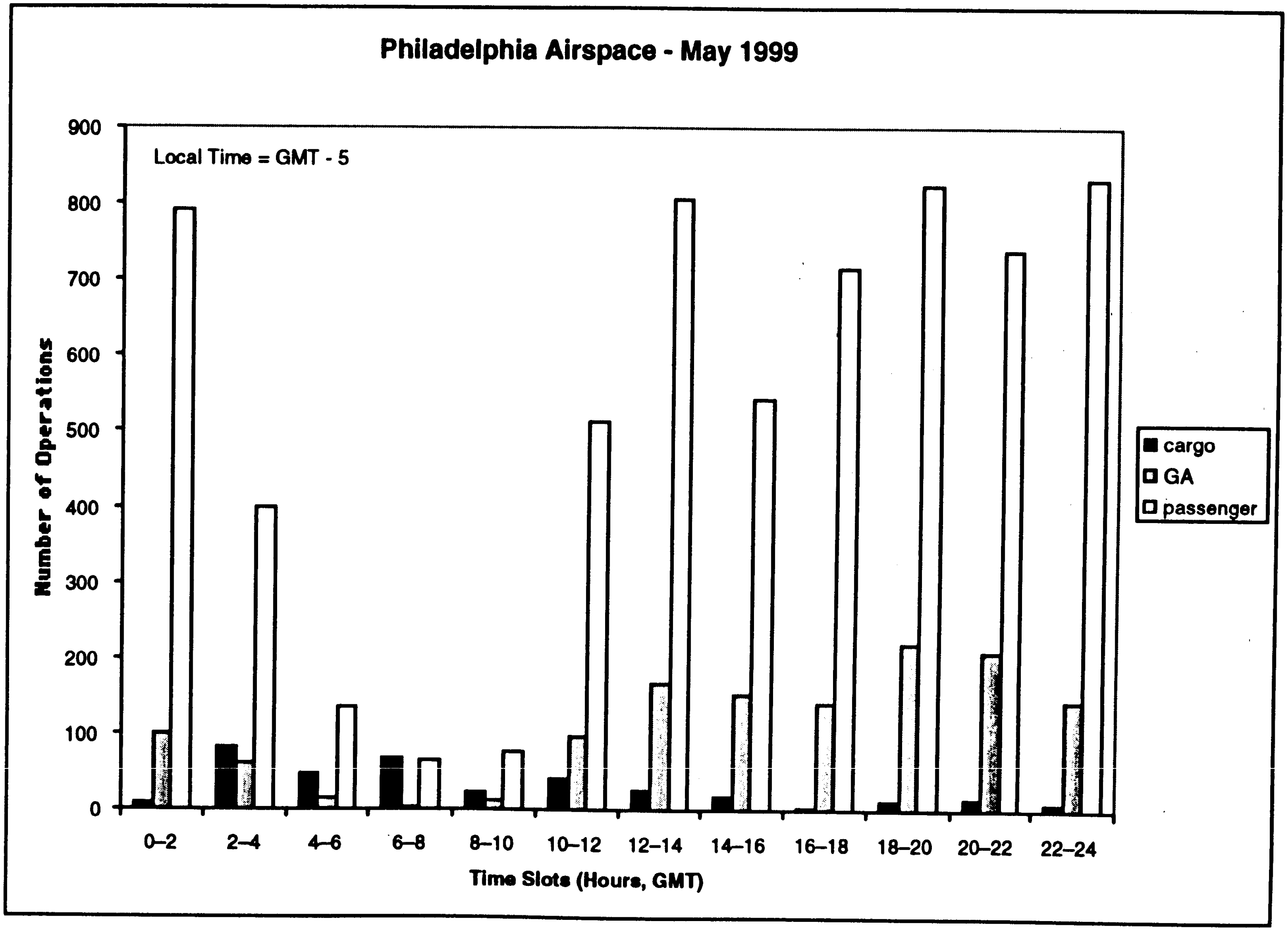

Figure C.13. Philadelphia Airspace – May 1999

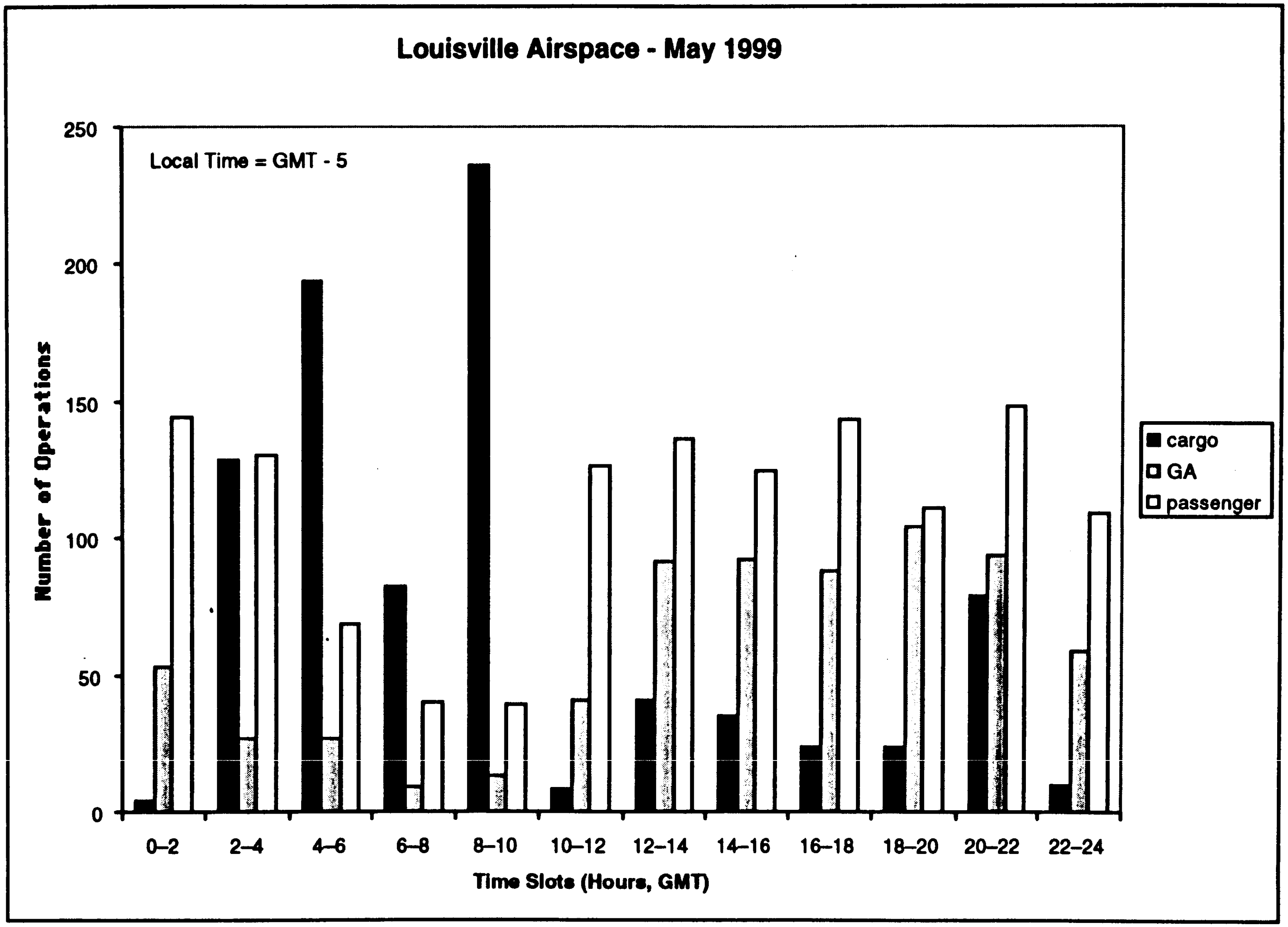

Figure C.14. Louisville Airspace – May 1999

Glossary

ACAS	Airborne Collision Avoidance System
ARTS	Automated Radar Terminal System
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
BTS	Bureau of Transportation Statistics
CAASD	Center For Advanced Aviation System Development
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
FIDS	FAA Incident Data System
GA	General Aviation
IFR	Instrument Flight Rules
MACs	Midair Collisions
NAS	National Airspace System
NASA	National Air and Space Administration
NMACs	Near Midair Collisions
NTSB	National Transportation Safety Board
RTM	Revenue Ton Miles
TCA	Terminal Control Area
TCAS	Traffic Alert and Collision Avoidance System
U.S.	United States
VFR	Visual Flight Rules